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Manual Fire Suppression Methods on Typical Machinery Space Spray Fires

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A series of tests was conducted to evaluate the effectiveness of Aqueous Film Forming Foam (AFFF), potassium bicarbonate powder (PKP) and Halon 1211, alone and in various combinations, in extinguishing spray fires. The sprays were generated by JP-5 jet fuel issuing from an open sounding tube, and open petcock, a leaking flange or a slit pipe and contacting an ignition source.

The results indicate that typical fuel spray fires, such as those simulated in this series, are very severe. Flame heights ranged from 6.1 m (20 ft) for the split pipe to 15.2 m (50 ft) for the sounding tube scenario. These large flame geometries were accompanied by heat release rates of 6 MW to greater than 50 MW, and hazardous thermal radiation levels in the near field environment, up to 9.1 m (30 ft) away.

Successful suppression of these fires requires both a significant reduction in flame radiation and delivery of a suppression agent to shielded areas. Of the nine suppression methods tested, the 95 gpm AFFF hand line and the hand line in conjunction with PKP were particularly effective in reducing the radiant flux.

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FOREWORD

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EXECUTIVE SUMMARY

BACKGROUND

Spray fires pose a unique and serious shipboard hazard. Significant personnel and equipment losses have resulted from hydrocarbon fuel and lubricant spray leak fires in shipboard machinery spaces. The severity of the hazard depends on a wide range of ignition and burning effects, enclosure geometries, and ventilation conditions. A typical spray fire is characterized by a momentum driven jet flame, a running fuel fire, and a two dimensional pool fire - nearly simultaneously. Imminent hazards associated with such an incident include a spreading pool fire, damage or ignition of remote materials and equipment and rapid decay of environmental conditions.

Current shipboard machinery space protection includes both fixed and mobile fire suppression systems, designed to control fires of different sizes. For example, potassium bicarbonate (PKP) hand-held portable extinguishers are available for use on incipient fires. A Twin Agent Fire Extinguishing System (TAFES) has been incorporated in machinery space fire protection systems to control running fuel and fuel spray fires (PKP side of TAFES), and bilge fires (aqueous film forming foam (AFFF) side of TAFES). AFFF sprinkler systems are also used to control bilge fires, and total flooding Halon 1301 systems, when available, are used to control large fires.

The PKP side of the TAFES (e.g. PKP storage container, PKP piping and hose, PKP nozzle, nitrogen cylinder and piping, etc.) has been plagued by maintainability and reliability problems. Due to the frequency of these problems, the utility of the PKP portion of the TAFES unit is in question. In order to assess the relative fire fighting capability of the PKP side of the TAFES unit, the effectiveness of the TAFES as well as other fire suppression methods was determined experimentally for selected spray fire exposures.

EXPERIMENTAL PROGRAM

A detailed review of prior test work indicated that while the TAFES unit had considerable effect on most test fires, it may not be the optimum method for suppressing spray fuel fires. In some cases when using the TAFES unit, complete extinguishment could not be achieved. In addition, while total flooding Halon 1301 successfully suppressed various spray fires, little cooling took place, requiring lengthy soak times to reduce surface temperatures in the machinery space below the autoignition temperature of the fuel. Therefore, a test program was designed and conducted to: (1) isolate and quantify various fuel spray fire scenarios, and (2) evaluate a number of manual suppression alternatives.

Large scale experiments were conducted at the Naval Research Laboratory facilities at the Chesapeake Bay Detachment. The experiments were conducted in two phases. As part of the first phase, preliminary tests were conducted to determine the general magnitude of specific spray fires and to define the qualitative effects of changes in fuel flow rate, fuel leak geometry, and orientation of the spray jet. Additional factors examined during these tests included intermittent and continuous ignition sources, and the effects of obstructions on fire intensity, flame stability, flame shielding and reignition (e.g. heated surfaces).

Specific spray leak scenarios were then tested under large scale free-burn conditions and measurements were taken in order to quantify selected thermophysical characteristics. The scenarios tested included:

(1) open sounding tube
(2) open petcock
(3) leaking flange, and
(4) slit pipe.

These scenarios were selected based on review of the Judge Advocate General reports of shipboard spray fire incidents. Measurements were taken to provide estimates of flame geometry and incident flux at various distances from the vertical centerline of the spray fires. The results of these tests were used to estimate the fuel burning rate, the impact of flame radiation on near-field survivability, and the potential for ignition of materials and equipment remote from the spray fire. State-of-the-art analytical techniques were used to estimate or predict the potential effects of these fires in a typical machinery space enclosure.

In the second phase, nine alternative methods of suppression were tested under two spray fire conditions. Included were:

(1) Twin agent fire extinguishing system (TAFES)
(2) AFFF side of TAFES unit
(3) AFFF side of TAFES unit and 12.2 kg
(27 lb) PKP portable extinguisher

(4) AFFF hand line
(5) AFFF hand line and PKP portable
(6) 12.2 kg (27 lb) PKP portable
(7) Two 12.2 kg (27 lb) PKP portable extinguishers, simultaneously
(8) Halon 1211 hand line, wide angle fog
(9) Two Halon 1211 portables, simultaneously.

Two scenarios were selected based on the results of Phase I; one scenario represented a typical, moderate spray fire condition resulting from a leaky pipe or petcock; the other represented an extremely severe case resulting from an uncapped sounding tube. Individual suppression alternatives were evaluated based on such factors as flame "knock-down", reduction in flame radiation, and whether or not extinguishment was accomplished.

RESULTS AND CONCLUSIONS

The results of these large scale tests indicate that typical fuel spray fires such as those simulated in this series are very severe. Flame heights ranged from 6.1 m (20 ft) for the slit pipe to 15.2 m (50 ft) for the sounding tube scenario. These large flame geometries were accompanied by heat release rates of 6 MW to greater than 50 MW, and hazardous thermal radiation levels in the near field environment, up to 9.1 m (30 ft) away. If unsuppressed, fires of these magnitudes could result in damage to electronics and machinery equipment, ignition of combustibles, and severe burn injuries to personnel located in the machinery space in just a few seconds. The actual time to hazardous conditions would depend on the arrangement of equipment and materials, the location of the personnel, and the enclosure and ventilation effects.

These spray fires were characterized predominantly by high flame radiation and shielded burning. Successful suppression of these fires required both a significant reduction in flame radiation and delivery of a suppression agent to shielded areas. Of the nine suppression methods tested, a significant reduction in radiant flux was achieved with the TAFES unit, the 95 gpm AFFF hand line, and the hand line in conjunction with a PKP portable extinguisher. The sounding tube fire was not fully extinguished, but thermal radiation was minimized and no significant shielded burning persisted.

The Twin Agent Fire Extinguishing System (TAFES) performed satisfactorily, but not as well as the AFFF hand line in conjunction with a PKP portable extinguisher. No qualitative difference in suppression action was observed when substituting a PKP portable extinguisher for the PKP side of the TAFES unit. Limited effectiveness was observed when either PKP or Halon 1211 was used without AFFF, demonstrating the effectiveness and necessity of using AFFF to cool the flame region and surfaces which could otherwise cause reignition.

Conclusions

(1) Typical fuel spray fires can produce heat release rates in excess of 50 MW, and produce hazardous conditions in seconds. The actual burning rate and time to hazard is dependent on the magnitude and orientation of the fuel leak spray, the ignition duration, the proximity of other equipment and obstructions, and enclosure and ventilation conditions.

(2) Discounting enclosure effects, the dominant hazard from such spray fires is flame radiation which can cause significant damage to electronics, equipment, and materials as well as burn injuries to personnel.

(3) Suppression of such fires required substantial flame cooling and agent delivery to shielded burn areas.

(4) Significant reduction in radiant flux occurred in tests with the TAFES unit, the 95 gpm AFFF hand line, and the hand line in conjunction with a 12.2 kg (27 lb) PKP portable extinguisher.

(5) No qualitative difference was observed when substituting a PKP portable extinguisher for the PKP side of the TAFES unit.

(6) Available deployment time for manual suppression is extremely short, frequently less than 30 seconds for the conditions developed in this test series.

(7) A significant reignition hazard existed if the surfaces on which the spray jet impinged were not cooled below the spontaneous ignition temperature of the fuel. AFFF in sufficient quantity was the only agent evaluated in this test series which demonstrated such capability.

While the results of these tests are encouraging regarding the control of fuel spray fires, additional issues have been identified which directly affect machinery space fire fighting and reentry guidelines for fuel spray fires. For example, typical spray fires may exceed the capabilities of current manual fire fighting techniques. In addition, environmental conditions may deteriorate so rapidly that the only feasible manual methods are those that can be effectively deployed <u>very quickly</u> (in seconds). Further complications include the potential rapid spread of the spray fire to combustible materials in the machinery space and the problem of reignition due to heated surfaces. Of particular concern is the effectiveness of total flooding suppression systems such as Halon 1301 and high expansion foam on deep seated burning of Class A combustibles, cables and electronic equipment, and of the inability of Halon 1301 to cool hot surfaces. These effects directly influence consideration for personnel reentry procedures as well as operational integrity.

Further testing and analysis are necessary to verify the effects of spray fires and methods of extinguishment. A major limitation of the tests conducted so far is the absence of any enclosure effects. To accurately assess fire hazard development due to fuel spray fires, and the impact of suppression candidates, tests should be performed in an enclosure which at least simulates the geometric and ventilation conditions expected in a machinery space. Such tests could provide quantitative data relative to survivability and damageability, the feasibility of manual fire fighting, the effectiveness of manual and fixed total flooding suppression methods, and hazards associated with reentry procedures.

Conceivably, the results of such tests would lead to selection of appropriate optimum suppression procedures, definition of criteria for maximum fire size for manual fire fighting, assessment of the potential effectiveness of current procedures and identification of necessary modifications to current machinery space fire fighting procedures. The results may also indicate the need for alternative measures for protection of machinery spaces and personnel from fuel spray fires.

MANUAL FIRE SUPPRESSION METHODS ON TYPICAL MACHINERY SPACE SPRAY FIRES

1. INTRODUCTION

Significant personnel and equipment loss‹s have resulted from hydrocarbon fuel and lubricant spray leak fires in shipboard machinery spaces. The potential for further losses is high, simply due to the operations which take place in this space, the nature and magnitude of such fires, and the availability of hydrocarbon fuels in large quantities.

Fuel spray fires pose a unique and serious hazardiin machinery spaces, as well as in engine rooms and other compartments where pressurized fuel and lubricant lines are located. The severity of the hazard depends on a wide range of ignition and burning effects, enclosure geometries, and ventilation conditions. In any event, a typical spray fire results in a momentum driven jet flame, a running fuel fire, and a two dimensional bilge pool fire - nearly simultaneously. Imminent hazards associated with such an incident include a spreading pool fire, damage or ignition of remote materials and equipment due to high flame radiation, and rapid decay of environmental conditions. DiNenno reported that untenable conditions were exceeded in less than a minute when a modest sized fuel spray fire was conducted in a full scale machinery space enclosure [1].

Fire fighting doctrine for Class B (flammable liquid) fires in machinery spaces was promulgated by the Naval Sea Systems Command (NAVSEASYSCOM) in 1985 [2]. The procedures outlined in the doctrine are based on review of fire incidents occurring in such spaces, the results of large scale tests on suppression of machinery space fires, and available fire fighting capabilities aboard Navy vessels.

Current shipboard machinery space protection developed under this doctrine includes both fixed and mobile fire suppression systems designed to control fires of different sizes. For example, potassium bicarbonate (PKP) hand-held portable extinguishers are available for use on incipient fires. A twin agent fire extinguishing system (TAFES), which combines the rapid flame knockdown characteristics of PKP with suppression characteristics of Aqueous Film Forming Foam

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(AFFF), has been incorporated in machinery space fire protection systems to control running fuel, fuel spray and bilge fires. AFFF sprinkler systems are also used to control bilge fires. Total flooding Halon 1301 systems, when available, are used to control large fires in which the space rapidly becomes untenable, limiting the effectiveness of manual fire fighting.

1.1 Problem Description

The TAFES unit was developed to control/extinguish three dimensional running or spray fuel fires. However, to minimize potential problems with visibility and breathing associated with discharging PKP at high flow rates within an enclosure, a maximum discharge rate of 2 lbs/s has been established for the TAFES unit.

The PKP portion of the twin agent fire extinguishing system (e.g. PKP storage container, PKP piping and hose, PKP nozzle, nitrogen cylinder and piping, etc.) has been plagued by maintainability and reliability problems.

Due to the frequency of these problems, the utility of the PKP portion of the TAFES unit is in question. The primary issue is whether or not the incremental fire fighting capability provided by the PKP side of the system justifies its continued use, in view of the other fire protection systems available for machinery spaces.

In order to address this issue, the effectiveness of the TAFES as well as other fire suppression methods was determined experimentally for representative spray fires that can occur in machinery spaces.

Factors considered in the evaluation of effectiveness included:

(1) suppression effectiveness
(2) limits of suppression capability
(3) conditions for survivability in the machinery space
(4) conditions for reentry
(5) damageability and continuity of operations.

1.2 Scope and Objectives

Insufficient data existed to quantify the effectiveness of AFFF and PKP in controlling/extinguishing spray fires due to fuel or lubricant leaks. Therefore, a research program was initiated to provide this data. The scope of this program included the study of the effectiveness of AFFF, PKP, and the TAFES unit on three dimensional spray fires which can typically occur in machinery spaces.

The primary objectives of this program were to:

(1) identify and quantify representative three dimensional spray fires and the concomitant hazards based on shipboard incidents and fuel transfer operations in machinery spaces (e.g. pressure, flow rate, spray leak geometry, spray leak orientation); and

(2) evaluate the capabilities and limitations of AFFF hand lines, twin agent fire extinguishing systems (TAFES) and a combination of an AFFF hand line and a portable PKP extinguisher.

Additional tests were conducted to evaluate suppression alternatives other than those associated with the TAFES unit in order to provide more comprehensive baseline data on suppression of spray fires.

2. BACKGROUND

2.1 Review of Spray Fire Incidents

A review of Navy Safety Center and Judge Advocate General fire incident reports for the period from 1961 to 1978 revealed a number (i.e., 27 incidents) of major spray fires on Navy ships. Most of the incidents occurred in either a machinery space or a fireroom, where leaks occurred in pressurized or gravity feed fuel or lubricant oil lines. All but one of the incidents involved Navy distillate fuel, JP-5, or lubricant oil. The prevalent ignition scenarios involved open sounding tubes, open or leaking petcocks, leaking flanges or a cracked pipewall or fitting. The incidents are summarized in Appendix A.

Considerable variation occurred among these cases in both the types of extinguishing agents used and in the fire fighting procedures. These variations dramatically influenced the time required to control and suppress these fires, and the resulting damage. Often, more than one extinguishing agent was used. The actual sequence and durations of multiple agent applications are not well documented, but selected information in the reports provides some anecdotal data on agent effectiveness under these severe conditions. For example, the reports consistently indicated that CO_2 extinguishers had provided no appreciable effect on these spray fires. However, in the four cases where potassium bicarbonate (PKP) extinguishers were used, the PKP agent appeared to have a significant impact on reduction in fire size, and in some cases, extinguishment.

2.2 Prior Spray Fire Testing

Two series of large scale spray fire tests were conducted earlier by the Navy in order to evaluate the effectiveness of selected extinguishing agents. The first series, which was conducted in 1964 by the Naval Research Laboratory (NRL) at the Damage Control Training Center, Philadelphia, examined the suppression capabilities of type 5 protein foam, PKP, protein foam and PKP in combination, and combined AFFF and PKP [3]. Two fire conditions were used:

(1) a low flow rate spray fire [37.8 l/min at 827 KPa (10 gpm at 120 psi)] with a bilge fire, and
(2) a high flow rate spray fire [56.7 l/min at 517 KPa (15 gpm at 75 psi)] without a simultaneous bilge fire. The tests were conducted with No. 2 diesel fuel as the fire source.

The results of this test series indicated that the combined effect of an AFFF hand line and a 13.6 kg (30 lb) PKP portable extinguisher was sufficient to suppress the low flow rate spray fire and the accompanying bilge fire. None of the suppression combinations resulted in extinguishment of the high flow rate spray fire, even in the absence of a bilge fire. It was concluded that typical protein foams remained relatively ineffective against three dimensional fuel spray fires, and that the "knock-down" capability of PKP is necessary when suppressing a fuel spray fire.

Kay reported on a second series of tests conducted at the same facility in 1973 [4]. As with the first series, the tests were conducted in a large scale concrete enclosure which simulated a shipboard machinery space. The fire exposure combined a spray fuel fire (Navy distillate fuel) discharged at 13.2 l/min (3.5 gpm) and 6894.7 KPa (1000 psi) and a 68.3 m^2 (735 ft^2) bilge fire using 340.7 l (90 gallons) of fuel over a water subsurface. In this test series, three fixed suppression systems were evaluated: total flooding Halon 1301, an AFFF sprinkler system, and total flooding high expansion foam.

A primary objective in this test series was to determine effective procedures for reentry after the space was initially abandoned. Therefore, efforts were made to replicate "worst case" fire conditions. This was accomplished by initially developing a fully involved bilge pool fire, then igniting the spray fire and providing a 30 s preburn period for the spray fire before suppression was initiated. The reentry team was equipped with a 380 mm (1 1/2 in.) AFFF hand line and an 8.1 kg (18 lb) PKP portable extinguisher. Efforts were made to reenter the space after operation of one of the fixed suppression systems, further suppress the fire, secure the fuel spray leak, and complete extinguishment.

The results of these tests indicated that an AFFF sprinkler system can be quite effective in controlling and suppressing a two-dimensional fuel spill fire. In addition, no apparent adverse effects were noted when the exhaust ventilation system was operated in order to reduce smoke concentrations to enhance reentry. However, while the AFFF sprinkler system provided considerable "cooling" of the environment and the hot surfaces in the test enclosure, it did not appear to satisfactorily extinguish the fuel spray fire itself. As in the earlier test series, the PKP portable extinguisher provided significant "knock-down" capability when discharged directly at the base of the spray jet. But, AFFF was needed to secure the pool fire and cool the enclosure before the spray fire could be approached by a fire fighter with a PKP portable extinguisher.

These tests also indicated qualitatively that a skilled fire fighter was able to provide similar extinguishment capabilities to the AFFF sprinkler system with a 340.2 l/min - 380 mm (90 gpm - 1 1/2 in.) AFFF hand line for the fire cases studied. But as with the AFFF sprinkler system, the spray fire could not be fully extinguished with AFFF alone.

The results from the tests with total flooding Halon 1301 indicated that Halon 1301 suppressed both the bilge and spray fires. However, Halon 1301 has essentially no cooling effect, so extensive "soak" times are required until hot surfaces within the enclosure cool below the autoignition temperature of the fuel. In addition, the enclosure must remain secured, with no leakage through openings or the ventilation system during this extended period, and the reentry team will be confronted with large quantities of combustion products and smoke particulate, significantly affecting visibility and requiring self-contained breathing apparatus.

Details of the performance of the high expansion foam systems were not provided, but it was concluded that such systems would not perform satisfactorily under conditions similar to those tested. In addition, concern was expressed regarding the adverse effects of high expansion foam on personnel, including disorientation, obscured vision and difficulty in breathing.

Beyond the effects of various suppression agents and methc s of application, this test series also demonstrated that:

(1) significant concentrations of smoke due to modest preburn periods (e.g. 30-45 s) dramatically affected visibility during reentry, and
(2) the burning rates of these fires are so rapid that ventilation controlled burning can be reached in a matter of seconds, effectively limiting the intensity of the fire, but resulting in increased volumes of toxic combustion products, such as CO, and increased smoke production throughout the entire space.

Eventually, such conditions could lead to burnout of the fire if the enclosure is relatively leak free, and the ventilation system is not operating - simply due to reduction of the oxygen concentration below that required for hydrocarbon fires (i.e., approximately 12%). Although allowing the fire to self extinguish may be a viable approach under some circumstances, one must also consider the effect of delays in reentry and the resultant extreme untenability of the space.

A third series of spray fire tests was conducted in 1986 in a large scale simulated machinery space facility at the Naval Technical Training Center, Treasure Island, CA [1]. These tests were part of a broader study of ventilation effects on enclosure tenability under fire conditions. In this series, the 24.6 l/min (6.5 gpm) spray fires [689 KPa (100 psi)], which were conducted in the lower level of the 9.1 m (30 ft) high test enclosure, were so severe that the fuel was shut off after approximately 60 seconds due to concern for the structural integrity of the facility. The results indicated that conditions deteriorated rapidly in the enclosure, resulting in high gas temperatures, and high CO and smoke concentrations - often in less than one minute - considerably limiting manual fire fighting capabilities.

Other studies by Sheehan [5] and Richards [6] provide additional results on the effectiveness of total flooding Halon 1301 and high expansion foam on machinery space fires, but the tests were limited to two dimensional bilge fires, providing no information on agent effectiveness on fuel spray fires.

More recent information on spray fire suppression in machinery spaces is included in a discussion paper prepared in January, 1986 [7]. This information is based on observations made during a series of training fires at the Fleet Training Center (FTC) San Diego Fire Fighting School in which some of the guidelines provided in Reference 2 were implemented in spray fire suppression training. While no measurements were taken, observations were consistent with results from the other studies reported here. For instance, the use of the AFFF side of the TAFES alone did not extinguish the spray fire. However, its cooling properties were necessary in conjunction with a steady stream of PKP directed at the base of the spray fire in order to achieve extinguishment. In addition, a PKP portable extinguisher was found to be more effective than the PKP side of the TAFES when used in conjunction with AFFF. This was attributed to:

(1) an increased working pressure for the 12.2 kg (27 lb) PKP portable extinguisher,
(2) continual application of the PKP rather than intermittent "bursts", and
(3) the increased maneuverability provided to the fire fighter(s) when using a portable extinguisher.

It was noted that for a number of the tests where insufficient cooling occurred, the fire fighters were forced to evacuate the space before extinguishment was achieved. In addition, the nature of the spray fire was such that there was virtually no growth period before the fire was burning at its peak rate.

2.3 Discussion

Careful review of the incident reports and the prior test results provided key input to the experimental plan. The incident reports confirmed that there is no single spray fire scenario. However, the experimental work indicated as would be expected, that spray fires exhibit many of the characteristics of typical, momentum driven three dimensional jet fires. For example, frequently the incipient growth period is extremely short, or non-existent. While one can not predict the flame geometry or orientation, typical spray fires produce exceedingly high heat release rates and flame radiation, resulting in survivability problems in a matter of seconds if the fire is not suppressed.

Critical mechanisms for suppressing a fuel spray fire include flame cooling, radiation shielding, oxygen deprivation, securing the ignition source and interference with the chemical reactions in the pyrolysis zone. Flame cooling and radiation shielding are also important from the standpoint of survivability, manual fire fighting capabilities, and ignition of materials remote from the spray fire itself.

The prior test programs, when examined collectively, indicated that while the TAFES unit had considerable effect on most of the test fires, it may not be the optimum method for suppressing spray fuel fires. In some cases, complete extinguishment could not be achieved with the TAFES unit. In addition, while total flooding Halon 1301 successfully suppressed the spray fires, little cooling took place, requiring lengthy soak times to reduce surface temperatures in the machinery space below the autoignition temperature of the fuel. In view of these considerations, a test plan was developed to:

(1) isolate and quantify various fuel spray fire scenarios, and
(2) evaluate a number of manual suppression alternatives.

3. EXPERIMENTAL DETAILS

3.1 Technical Approach

Large scale experiments were conducted at the Naval Research Laboratory facilities at the Chesapeake Bay Detachment. A primary objective was to evaluate the impact of the PKP side of the TAFES unit on representative fuel spray fires.

Review of the prior work and recent incident reports indicated that considerable variation might be expected in fuel leak geometry, the magnitude of the resulting hazard, and the effectiveness of alternative suppression methods in actual spray fires aboard ship. Therefore, in order to make these tests as realistic as possible, various fuel leak geometries and a number of suppression alternatives were examined. The fuel leak geometries were selected based on review of JAG reports and discussions with NAVSEA engineers. The suppression alternatives were selected based on current fire fighting doctrine and current or potential availability of a particular fire suppression alternative for use in machinery spaces.

The experiments were conducted in two phases. In the first phase, initial tests were conducted to determine the general magnitude of specific spray fires, and to assess the effects of changes in fuel flow rate, fuel leak geometry, and orientation of the spray jet. Additional factors examined during these tests included intermittent and continuous ignition sources, and the effects of obstructions on fire intensity, flame stability, flame shielding and reignition due to heated surfaces. Information developed in the initial tests provided guidance for parameter selection in the remaining tests.

Specific spray leak scenarios were then tested under large scale free-burn conditions, and measurements were taken in order to quantify selected physical and thermophysical characteristics. The tests were conducted in the open (i.e., free burn condition); no attempt was made to incorporate enclosure effects in this test series. Measurements were taken to provide estimates of flame geometry and incident flux at various distances from the vertical center line of the spray fire. The results of these tests were used to estimate the fuel burning rate, the impact of flame radiation on near-field survivability, and the potential for ignition of materials and equipment remote from the spray fire. State-of-the-art analytical techniques were used to estimate or predict the potential effects of these fires in a typical machinery space enclosure.

In the second phase, various methods of suppression were tested under two spray fire scenarios. The two scenarios were selected based on the results from Phase I; one scenario represented a typical, moderate spray fire condition resulting from a leaky pipe or petcock; the other represented an extremely severe case resulting from an uncapped sounding tube. Individual suppression alternatives were evaluated based on such factors as flame "knock-down", reduction in flame radiation, and whether or not extinguishment was accomplished. In addition, though difficult to quantify, such factors as speed of knockdown, mobility and flexibility, and levels of discomfort - all related to manual fire fighting, were considered.

3.2 Test Facility, Experimental Setup

The test apparatus was set up on an open concrete deck. As shown in Figs. 1, 2 and 3, a simulated overhead with various obstructions was located above the deck. This overhead consisted of a steel grate welded to the top of four steel supports 3.0 m (10 ft) off the ground. Located behind the overhead were two other steel grates which stood on end against a cinder block debris pile/wall. On top of the debris pile was a steel roof which sloped towards the overhead.

JP-5 fuel was used throughout this test series due to its extensive use in gas turbine engines, its flash point, which is similar to Navy distillate fuel (DFM), and its immediate availability at CBD.

A 2.1 m (7 ft) by 2.1 m (7 ft) by 0.3 m (1 ft) deep steel collection pan was located under the overhead. The fuel (JP-5) was piped from the fuel pump house to the center of this collection pan. The fuel supply pipe was elbowed and turned straight up. A 0.1 m^2 (1 ft^2) piece of steel on two cinder blocks was used as a base to support the piping and to hold a 0.3 m (1 ft) diameter ignition pan. The various devices used to provide selected spray leak geometries were positioned 0.91 m (3 ft) above the deck.

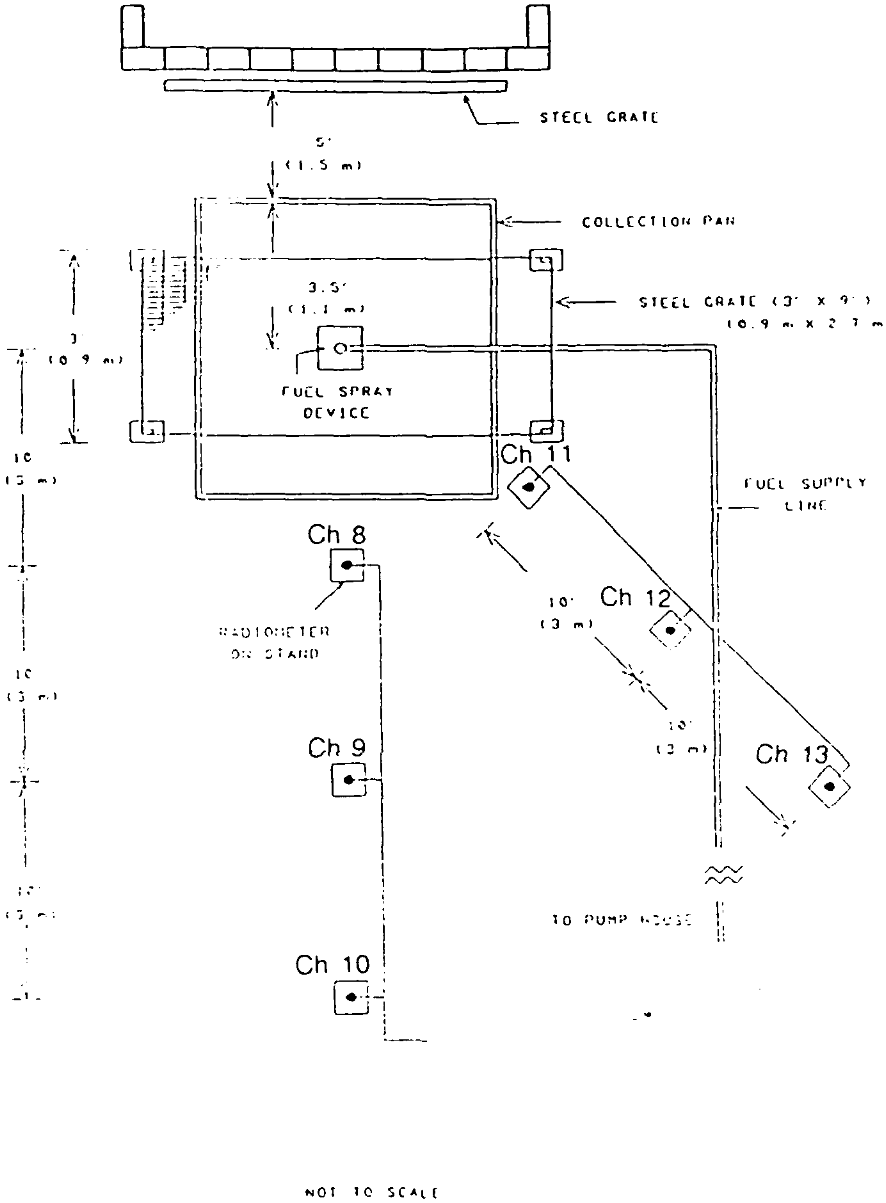

Fig.1 Plan view of experimental set up

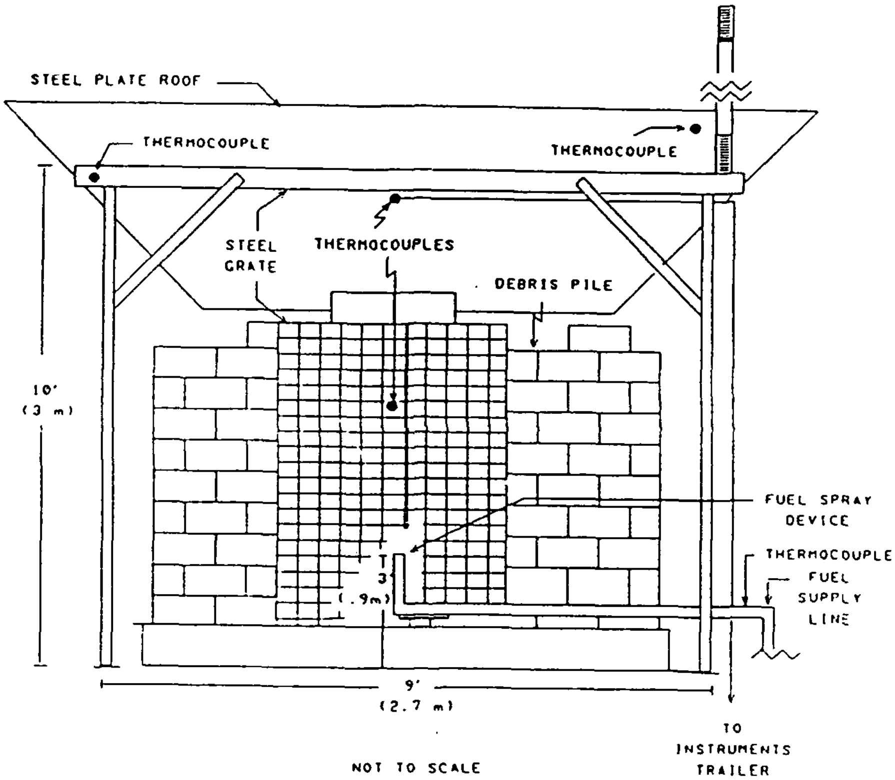

Fig.2 Elevation view of experimental set up

Fig.3 Photograph of experimental set up

3.3 Instrumentation

Fourteen channels of data were taken during these tests. Measurements included: static pressure at the fuel leak opening, temperature at six locations and thermal radiation at six locations as shown in Figs. 1 and 2. All instrument signals were read by a Hewlett Packard scanner, model number HP-3497A. A thermocouple card with reference junction temperature compensation was used to measure the millivolt readings from the thermocouples. The same type of card with no compensation was used to measure the millivolt outputs of the radiometers and pressure transducer. This scanner was interfaced with a Hewlett Packard computer, model HP-3896, to facilitate both conversion and storage of the data to floppy disk. In this test series, data were taken approximately every three seconds. Table 1 provides a summary of the instrumentation. Figs. 1 and 2 illustrate measurement locations.

Type K inconel sheathed thermocouples (Omega Model Cain-116U-12) were used in these tests because of the harsh environment where temperature measurements were needed. The temperatures recorded during the tests were calculated directly from the compensated millivolt readings using an eighth order polynomial fit. This resulted in temperatures in degrees Celsius, which were then converted to Fahrenheit and stored.

A total of six water-cooled radiometers, Medtherm models 64-10-19, 64-20-19 and 64-30-19, were used to measure the thermal radiation from the spray fires. Two sets of three radiometers were placed at 3.0 m (10 ft) intervals from the origin of the fuel spray. One set was located 45 degrees from the other set of radiometers to determine the extent of reproducibility in the radiation measurements when viewing the fire from different angles. The radiometers were angled to allow the full height of the flame to be within the 150 degree viewing angle of the radiometers.

Pressure measurements were taken using a 6.3 mm (1/4 in.) static line to keep the pressure transducer remote from the fire area. The static line was connected near the fuel spray source for the sounding tube and petcock fires. No pressure readings were taken for the slit pipe fires because of the piping arrangement used. A Vitran model 118 pressure transducer with a 10V excitation was used for all tests in which pressure measurements were recorded.

Table 1 - Test Instrumentation

Description	Instrument Type	Units	Channel Number Tests 1-10	 Tests 11-24	 Tests 25-36	Calibration
Ambient Temp	Type K Thermocouple	F	1	1	1	N/A
Fuel Temp	Type K Thermocouple	F	2	2	2	N/A
Temp Below Grating	Type K Thermocouple	F	3	3	4	N/A
Pipe Temp	Type K Thermocouple	F	4	4	5	N/A
S. Grating Temp	Type K Thermocouple	F	5	5	6	N/A
10 ft Flame Temp	Type K Thermocouple	F	6	6	3	N/A
Flux 10 ft	Radiometer	kW/m^2	8	8	8	23.4 $kW/m^2/mV$
Flux 20 ft	Radiometer	kW/m^2	9	10	9	19.1 $kW/m^2/mV$
Flux 30 ft	Radiometer	kW/m^2	10	9	10	19.3 $kW/m^2/mV$
Flux 10 ft 45	Radiometer	kW/m^2	11	11	11	24.7 $kW/m^2/mV$
Flux 20 ft 45	Radiometer	kW/m^2	12	12	12	18.8 $kW/m^2/mV$
Flux 30 ft 45	Radiometer	kW/m^2	13	13	13	19.3 $kW/m^2/mV$
Nozzle Press	Pressure Transducer	PSI	14	14	14	

In addition to the data collected and stored on the computer, color video documentation of the tests was recorded. Due to the size of these fires, flame heights were recorded by a remote video camera instead of using thermocouples. A scale was mounted 1.2 m (4 ft) in front of the camera in direct line with the fire. This scale was calibrated by placing a 7.6 m (25 ft) pipe with 0.3 m (1 ft) and 1.5 m (5 ft) increments clearly marked at the spray source. Heights of 3.0, 4.5, 6.1, and 7.6 m (10, 15, 20 and 25 ft) were marked using this method. The average length of the 1.5 m (5 ft) intervals was then used to extrapolate the remaining heights. By marking the camera location and securing the scale in place, the calibration was maintained between tests. In addition to providing an alternative angle for evaluating flame geometry, a second video camera recorded the effects (e.g. ignition points) of thermal radiation on material samples placed at 3.0 and 6.1 m (10 and 20 ft) from the fuel spray source. The material samples were only included in selected tests, to provide some information on autoignition of materials due to thermal radiation by spray type fuel fires. Material samples, including newsprint, corrugated cardboard, unpainted plywood, standard PVC insulated cable, special PVC insulated cable and crosslinked polypropylene insulated low-smoke producing cables were mounted to the vertical surfaces of the test stands. The test stands were painted black to minimize radiation effects on the samples due to reflection from the test stands.

3.4 Key Experimental Parameters

3.4.1 Representative Fire Scenarios

As discussed in the introduction, one could imagine an infinite number of spray leak scenarios which could occur in a typical shipboard machinery space. Four scenarios were initially selected for testing in the preliminary series. Included were:

(1) open sounding tube,
(2) open petcock,
(3) leaking flange, and
(4) slit pipe.

The selection of these four cases was based on review of Navy Safety Center and Judge Advocate General fire incident reports, and discussions with Navy Department fire protection specialists and researchers. The first three scenarios represent actual cases where serious loss of life and/or equipment damage occurred. The slit pipe is representative of a scenario used for training purposes, and served as a baseline case for comparing the other scenarios to a case which is familiar to shipboard Navy personnel.

Open Sounding Tube Scenario

A 18.9 mm (0.75 in.) diameter black iron pipe and gate valve assembly was oriented to provide an upward, roughly axisymmetric spray of fuel, simulating a sounding tube with the cap removed. The resulting fire is shown in Fig. 4.

Open Petcock Scenario

A petcock valve with a 6.3 mm (0.125 in.) opening was positioned on the end of a piece of vertically oriented pipe, again to simulate an upward spray leak.

Leaking Flange Scenario

A split gasket was installed in a pipe flange, providing a fuel leak around the flange. The slit was oriented to provide two spray leak directions, one approximately 25 degrees downward and the other 90 degrees downward from the horizontal plane.

Slit Pipe Scenario

A 18.9 mm (0.75 in.) long slit (approximately the thickness of a hacksaw blade) was cut in the wall of a horizontally oriented piece of nominal one inch diameter cast iron pipe near the capped end. Three different spray leak orientations were considered. A vertical spray orientation resulted in fuel spray impingement on the overhead steel grate; horizontal and 45 degrees above horizontal spray orientations sprayed fuel on the debris pile wall and roof, and the steel grates standing against the wall, as shown in Fig. 5.

3.4.2 Obstructions

Obstructions can significantly affect the burning characteristics of a spray fire. Vertical and horizontal surfaces, pipe runs, and overhead cable trays can actually enhance the burning of a fuel spray fire by further breaking up the spray droplets, and redirecting the sprays. These surfaces can also serve as flame holders, stabilizing what would otherwise be a very unstable jet spray fire - increasing the difficulty of suppression. As the fire heats these surfaces, they may serve as reignition sources.

Therefore, for selected tests, obstructions were placed approximately 3.0 m (10 ft) overhead (e.g. to simulate the grated steel deck of the upper level in a machinery space) and behind the fire source (e.g. to simulate a vertical bulkhead surface), with the spray fires directed at the obstructions. In some cases, when the fires were

Fig.4 Photograph of typical experimental sounding tube fire

Fig.5 Photograph of typical experimental slit pipe fire

extinguished, the fuel spray was continued, to check the possibility of reignition from the heated obstructions.

3.4.3 Ignition Sources

Two ignition modes were used in this test series. One mode involved manual ignition of the fuel spray by a fuel soaked cotton torch; the torch was removed immediately after sustained burning was achieved, representing an intermittent or transient ignition source. The other mode involved exposure of the torch ignited spray fire to a pilot flame from a 0.3 m (1 ft) diameter fuel fire in a burnback pan, simulating a continuous ignition source.

3.4.4 Alternative Suppression Methods

Nine manual suppression alternatives were examined in this test series:

(1) Twin agent fire extinguishing system (TAFES-AFFF and PKP);
(2) AFFF side of TAFES unit;
(3) AFFF side of TAFES unit plus a 12.2 kg (27 lb) PKP portable;
(4) AFFF hand line;
(5) AFFF hand line plus a PKP portable;
(6) 12.2 kg (27 lb) PKP portable;
(7) Two 12.2 kg (27 lb) PKP portables, simultaneously;
(8) Halon 1211 hand line, wide angle fog; and,
(9) Two Halon 1211 portables, simultaneously.

Table 2 provides information on discharge rates and durations. As indicated in Table 2, the 95 gpm hand line delivers over 50% more AFFF than the AFFF side of the TAFES. However, the PKP flow rate from the portable extinguisher is the same as that of the TAFES unit. Since the combination of the 95 gpm AFFF hand line and the portable PKP extinguisher also affords greater maneuverability on the part of the fire fighters than the TAFES, it was expected that this combination would perform somewhat better than the TAFES.

3.5 Experimental Procedure

Prior to the fuel being turned on, the data collection system and video cameras were started. The fuel supply pump was then started and the resultant spray of JP-5 fuel was ignited with the small fuel soaked cotton torch. In the preliminary and non-suppression tests conducted in Phase I, the fires were allowed to burn for two minutes before the fuel was secured by turning the fuel supply pump off. Any remaining pool fire was extinguished using an AFFF hand line. This was done a number of times for each of the spray scenarios, under different spray direction orientations. Fuel flow rate and quantity data were collected manually and recorded for each test using the gallons counter on the fuel pump and a stop watch.

Table 2 - Alternative Manual Suppression Methods

Suppression Method	Exting. Agent	Discharge Rate	Maximum Duration (Seconds)
TAFES Unit	AFFF	227 l/min (60 gpm)	120
	PKP	0.9 kg/s (2 lb/s)	2 s bursts
AFFF Hand Line	AFFF	359 l/min (95 gpm)	120
PKP Portable	PKP	0.9 kg/s (2 lb/s)	15
Halon 1211 Hand Line	Halon 1211	1.3 kg/s (3 lb/s)	50
Halon 1211 Portable	Halon 1211	0.9 kg/s (2 lb/s)	15

For the suppression tests in Phase II, the above procedure was repeated except that after ignition, the fuel was allowed to preburn for 30 seconds before agent application was started. Agent application was started when the fire fighter was 6.1 m (20 ft) from the base of the fuel spray. He was then allowed to advance to within 3.0 m (10 ft) of the base. Agent was applied until the fire was extinguished, the agent was expended, or the preselected two minute duration was reached. The fuel was secured and any remaining pool fire or hot spots were extinguished or cooled using an AFFF hand line.

4. RESULTS

4.1 Preliminary Testing

The preliminary tests conducted in Phase I were to characterize the magnitude of the "spray fire" and to qualitatively examine the effects of changes in first order parameters such as fuel flow rate, spray direction, ignition mode, and obstructions. The results from these tests provided guidance regarding a more detailed approach to studying control of machinery space fuel spray fires, and information on the effects of specific fire fighting agents and methods.

In general, very low fuel flow rates resulted in a running fuel condition, and a fire that was primarily a two dimensional pool fire. This was observed for the sounding

tube leak at 33.2 l/min (8.8 gpm), for the petcock leak at 7.5 l/min (2 gpm), and the flange gasket leak at 9.8 l/min (2.6 gpm). In these cases, the pressure was nominally 227.5 KPa (33 psi).

However, at relatively higher flow rates [sounding tube at 87-196.5 l/min (23-52 gpm); petcock 24.9 l/min (6.6 gpm); slit pipe 20.8 l/min (5.5 gpm)] in the same pressure range [158-220 KPa (28-32 psi)], the fires were characterized by a three dimensional fuel spray jet fire. Figures 4 and 5 show typical experimental sounding tube and slit pipe fires. <u>These fires were considerably larger than anticipated.</u> For example, the sounding tube spray leak fire at 196.5 l/min (52 gpm) resulted in a spray fire jet on the order of 12.2-15.2 m (40-50 ft) high. A conservative estimate of the heat release rate for this fire is 50 to 60 MW (17 to 20.5 x 10^7 BTU/hr) assuming that approximately 50% of the fuel in the jet is burned. Radiation levels forced observers stationed 6.1 m (20 ft) away to retreat. This was particularly alarming when considering that the tests were conducted in the open. One would expect more severe conditions if these fires were conducted in an enclosure, such as a machinery space.

All of the spray fires were characterized by an essentially nonexistent growth phase. That is, ignition of the spray resulted in an instantaneous, quasi-steady heat release rate. This means that the time delays associated with manual fire fighting may be critical relative to machinery space tenability and equipment damage control.

The ignition mode and position of obstructions significantly influenced the intensity of the spray fires. While the transient ignition source generated sufficient heat energy to ignite the fuel sprays, visible burning usually occurred at some distance away from the leak itself. However, under conditions where a continuous ignition source was provided near the leak, burning was observed along the entire jet spray, and radiation levels were noticeably higher.

As predicted, obstructions (simulating overhead walkways, bulkheads, and equipment surfaces) tended to break up the sprays, enhancing the burning rate, and serving to stabilize the flames. In addition, once the obstructions were sufficiently heated from the initial spray fire, they served as a source of energy to reignite the jet spray after it had been successfully extinguished.

4.2 Phase I - Spray Fires Tests

Based on the results of the preliminary tests, a series of fourteen large scale tests was designed to quantify the relative fire intensities and related hazards for selected spray fire scenarios. Three spray leak geometries were tested: the slit pipe, the open petcock and the uncapped sounding tube. Since the preliminary tests indicated that the leaking flange gasket scenario would result primarily in a running fuel and pool fire (in the flow and pressure ranges tested) it was not included. Obstructions were included for all of the tests, as described in Section 3. Eight of the fourteen tests involved a continuous ignition source; the remaining tests had an intermittent ignition, resulting in lower burning rates and lower thermal radiation output due to discontinuous flame geometries. Examination of the incident flux data from the radiometers provides a rough estimate of a 30% reduction in burning rate when the continuous ignition source was not used. Table 3 provides a summary of the tests and selected results.

4.2.1 Flame Heights and Burning Rates

Flame heights, ranging from 6.1 to 15.2 m (20 to 50 ft) were measured and recorded for the various tests in Phase 1 (see Table 3).

Experimental correlations are available which relate flame height and geometry (e.g. thickness) to burning rate [8,9]. However, these correlations apply only to pool fire geometries, neglecting the momentum effects which dominate fuel spray jet fires such as those studied here.

While of limited value in quantifying the burning rate, the estimated flame heights provided an important measure of flame size for each of the spray geometries tested. For example, the sounding tube spray fire resulted in a flame plume of approximately 15.2 m (50 ft). Obviously, this fire would extend to the overhead of a typical machinery space, spreading horizontally along the overhead and increasing the potential for ignition of materials. Smaller fires, such as the slit pipe which resulted in a spray angled at 45 degrees from the horizontal, probably would not reach the overhead of the enclosure [overhead height typically 9.1 m (30 ft)] and consequently pose less of a threat to combustibles along the ceiling at remote distances from the fire. However, the spray would most likely expose equipment, electronics, and materials in the vicinity of the fire to flame, noncombusted fuel and high thermal radiation.

Since the use of pool fire correlations for predicting burning rate was deemed inappropriate, a simple method was used to provide approximate heat release rates for each of the spray fire geometries tested. The ideal heat release rate was calculated from the expression:

TABLE 3. PHASE I SPRAY FIRE TESTS

TEST NO.	GEOMETRY	DIRECTION	IGNITION	FLOW RATE	AMB TEMP	WIND	FLAME HEIGHT
SF 001	SOUNDING TUBE	STRAIGHT UP	CONTINUOUS	196 l/min 52 GPM	4 C (40 F)	4-8 KN N	15.2 m (50 FT)
SF 002	SOUNDING TUBE	STRAIGHT UP	CONTINUOUS	196 l/min 52 GPM	4 C (40 F)	4-8 KN N	15.2 m (50 FT)
SF 003	SOUNDING TUBE	STRAIGHT UP	CONTINUOUS	196 l/min 52 GPM	4 C (40 F)	4-8 KN N	15.2 m (50 FT)
SF 004	SOUNDING TUBE	STRAIGHT UP	CONTINUOUS	196 l/min 52 GPM	4 C (40 F)	4-8 KN N	15.2 m (50 FT)
SF 005	PETCOCK	STRAIGHT UP	CONTINUOUS	25 l/min 6.6 GPM	4 C (40 F)	5-10 KN N-NE	7.6 m (25 FT)
SF 006	PETCOCK	STRAIGHT UP	CONTINUOUS	7.5 l/min 2 GPM	3 C (38 F)	5-10 KN N-NE	7.6 m (25 FT)
SF 007	SLIT PIPE	STRAIGHT UP	CONTINUOUS	18.9 l/min 5 GPM	3 C (38 F)	5-10 KN N-NE	10.6 m (35 FT)
SF 008	SLIT PIPE	45 INTO DEBRIS PILE	CONTINUOUS	20.8 l/min 5.5 GPM	3 C (38 F)	5-10 KN N-NE	6.1 m (20 FT)
SF 009	SLIT PIPE	45 INTO DEBRIS PILE	INTERMITTENT	19.6 l/min 5.2 GPM	3 C (38 F)	5-10 KN N-NE	6.1 m (20 FT)
SF 010	SLIT PIPE	STRAIGHT UP	INTERMITTENT	19.6 l/min 5.2 GPM	3 C (38 F)	5-10 KN N-NE	10.6 m (35 FT)
SF 011	PETCOCK	STRAIGHT UP	INTERMITTENT	25.7 l/min 6.8 GPM	3 C (38 F)	5-10 KN N-NE	7.6 m (25 FT)
SF 012	PETCOCK	STRAIGHT UP	INTERMITTENT	25.7 l/min 6.8 GPM	3 C (38 F)	5-10 KN N-NE	7.6 m (25 FT)
SF 013	SOUNDING TUBE	STRAIGHT UP	INTERMITTENT	189 l/min 50 GPM	3 C (38 F)	5-10 KN N-NE	15.2 m (50 FT)
SF 014	SOUNDING TUBE	STRAIGHT UP	INTERMITTENT	127.7 l/min 33.0 GPM	3 C (38 F)	5-10 KN N-NE	15.2 m (50 FT)

TABLE 3. PHASE I SPRAY FIRE TESTS (CONTINUED)

TEST NO.	ESTIMATED HEAT RELEASE RATE MW	BTU/SEC X1000	NOTES
SF 001	55.6	52.70	MATERIAL SAMPLES IGNITED AT 3 m (10 FT)
SF 002	55.6	52.70	SOME MATERIAL CHARED AT 6m (20 FT), NO SAMPLES AT 3m (10 FT)
SF 003	55.6	52.70	
SF 004	55.6	52.70	
SF 005	7.1	6.7	FULL OPEN, WIND EFFECTS SIGNIFICANT
SF 006	2.1	2	ONE-HALF OPEN, POOL FIRE AFTER 1.5 MIN, WIND PUSHED FLAME TOWARDS DEBRIS PILE
SF 007	5.9	5.59	NO MATERIAL SAMPLE DAMAGE AT 3, 4.5 AND 6m (10,15 AND 20 FT)
SF 008	5.9	5.59	MATERIAL SAMPLE IGNITED AT 3m (10 FT)
SF 009	3.9	3.7	WIND PUSHED FLAME AWAY FROM MATERIAL SAMPLE
SF 010	3.9	3.9	
SF 011	4.7	4.4	FULL OPEN
SF 012	1.4	1.3	CLOSED 2 TURNS
SF 013	36.7	34.8	FULL OPEN, MATERIALS AT 6m (20 FT) IGNITED AND BURNED
SF 014	23.3	22.1	ONE-HALF CLOSED, MATERIALS AT 6m (20 FT) IGNITED

$$\dot{Q} = \Delta H_c \cdot \dot{m}$$

where $\dot{Q}$ = heat release rate kW (Btu/s)

ΔH_c = net heat of combustion for JP-5 43.29×10^4 KJ/kg (18.63×10^3 Btu/lb)

$\dot{m}$ = mass flow rate of the fuel kg/s (lb/s)

Assuming an average fuel density of 785.2 kg/m^3 (49 lb/ft^3), the expression can be reduced to:

$$\dot{Q} = 33.9 \times 10^5 \cdot l/s$$

where l/s = liters per second fuel flow rate.

The equation above was used to calculate the ideal heat release rate for each test. However, it was estimated that under continuous ignition approximately 50 percent of the fuel actually burned in the jet fires. The remainder of the fuel spray was either blown away or fell to the concrete surface (in some cases creating a pool fire). It was also observed that for the cases of intermittent ignition, the burning efficiency was even lower, being estimated at approximately one-third of the total fuel available. The estimated heat release rates tabulated in Table 3 are adjusted to reflect the incomplete combustion of available fuel; 50 percent efficiency was assumed for tests with continuous ignition and 33 percent was assumed for cases with intermittent ignition.

4.2.2 <u>Thermal Radiation</u>

A dominant hazard in the initial stages of a fuel leak spray fire is the radiant heat transferred to the surrounding environment. The tests conducted in this series indicate that incipient fire growth is relatively short. In a matter of seconds the fires grew to a quasi-steady maximum size unless changes occurred in the ignition source or the fuel spray geometry. Under this condition, relatively high levels of thermal radiation are transferred to available surfaces, resulting in potential: (1) ignition of materials at remote distances from the spray leak fire, (2) damage to electronics and machine equipment, and (3) difficult fire fighting conditions.

In order to assess the potential impact of thermal radiation from the jet flame on the surrounding environment, radiometers were positioned at various distances from the centerline areas of the fuel spray leaks. Measurements for each test are included in Appendix C.

The incident thermal radiation measured experimentally was used to calculate the radiative environment for each of the spray fire scenarios. As can be seen by reviewing the plots in Appendix C, variations in incident flux occurred for radiometers positioned at the same distance from the fire, depending on their line of sight. Ideally one would expect these measurements to be identical. However, the pulsing nature of the spray fires and the changes in fuel spray orientation and ambient wind conditions resulted in a nonaxisymmetric fire plume, and as a result, variations in incident flux. To compensate for these differences, the peak irradiance levels at 3.0, 6.1, and 9.1 m (10, 20 and 30 ft) from the base of the fire were each averaged for the two lines of sight, for a time period of relatively high, stable irradiance. Based on this approach, peak values were determined for incident radiation at different horizontal distances for each of the scenarios.

While variations in results were apparent among the fourteen tests conducted in Phase I, appropriate differences in fire intensity, flame geometry, and the effects of obstructions can be represented by three of the tested scenarios. Table 4 provides a tabulation of peak incident radiation levels for these three scenarios: the fully open uncapped sounding tube (SF001-004), the fully open petcock valve (SF005) and the slit pipe (SF007). All of these cases were tested under continuous ignition and with structural obstructions.

In order to estimate the radiative environment in the vicinity of these spray fires a "solid flame" method for calculating distance-dependent radiation was employed. In using this technique, the incident flux at a given distance is determined from the product of the flame emissive power, a view factor which considers the detailed geometry of the flame-target arrangement, and the flame temperature. This technique produces more accurate results, especially when the target distance is close to the fire, than do other techniques such as the point-source method [10].

Table 4 - Peak Irradiance (kW/m^2)

Spray Type	Distance From Fire m (ft) 3.0(10)	6.1(20)	9.1(30)
Sounding Tube	65.5	38.0	20.0
Petcock	28.3	13.4	6.3
Slit Pipe	20.0	12.6	4.9

The solid-flame method can be expressed as the Stefan-Boltzmann Equation [11]:

$$\dot{q}_i'' = F \tau \epsilon_f \sigma T_f^4$$

where: $\dot{q}_i''$ = incident radiation on target (kW/m^2)

F = Geometric view factor

τ = atmospheric transmittance

ϵ_f = flame emissivity

σ = Stefan-Boltzmann constant (5.669×10^{-5} kW/m^2)

T_f = flame temperature (°K).

For our purposes simplifications were made to this expression. First, the atmospheric transmittance term was assumed equal to one. This results in a slightly conservative estimate. Secondly, a flame emissivity of one was assumed, a reasonable assumption for thick hydrocarbon flames. The simplified expression used to calculate incident flux was:

$$\dot{q}_i'' = F \sigma T_f^4$$

The results of these calculations are plotted in Fig. 6. The view factors were calculated assuming a cylindrical flame geometry and a flat surface target. The calculated values are in good agreement with the measured flux at 3.0, 4.5, 6.1, and 9.1 m (10, 20 and 30 ft) for each of the three scenarios (see Table 4).

As can be seen in Fig. 6, the emissive powers from these flame jets result in thermal radiation levels that are quite high. The sounding tube simulation resulted in irradiance levels over twice as high as the slit pipe or petcock tests. While the petcock fire was slightly more severe than the slit pipe fire, they produced similar thermal radiation.

4.2.3 Hazard Impact of Thermal Radiation

The magnitude of fuel spray leak fires has obvious damage and injury implications. Radiant ignition of combustibles outside the flame envelope contributes to rapid

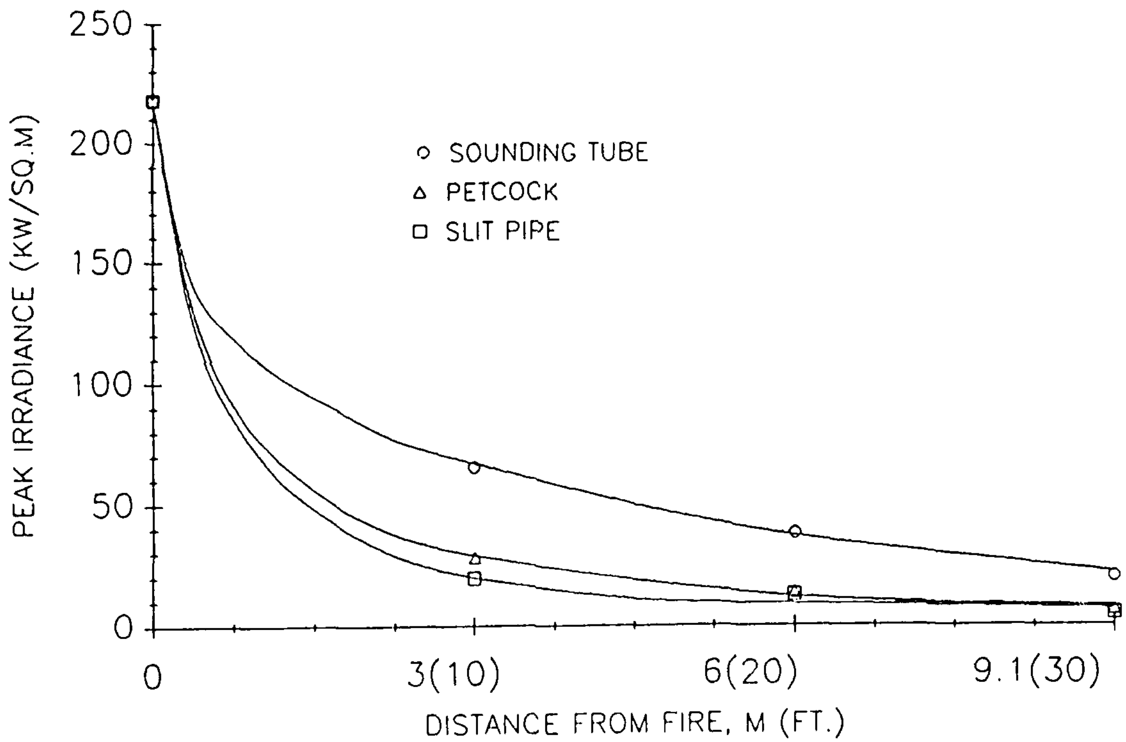

Fig. 6 Peak Radiation Levels for Selected Spray Fires

fire growth and spread. Additionally, the levels of thermal radiation can impede fire fighting, cause serious injuries to occupants of the space where such a fire occurs, and result in extensive damage to electronics and machine equipment if not suppressed quickly.

An analysis was conducted to provide information on the potential hazards of thermal radiation from the types of spray fires tested in this series. The focus of this analysis was on safe separation distance relative to ignition of combustibles and burn injuries under non-suppression conditions.

4.2.3.1 Material and Equipment Exposure Hazard

If a material, an equipment cabinet, or a piece of machinery is subjected to a thermal radiation insult, the surface temperature will increase. At the same time the surface is cooled by convection and conduction. The damage threshold is related to a temperature level, which in turn depends upon these heat transfer processes, the geometry and thermal inertia of the item, and the time of exposure. Analyses which incorporate these elements are typically reserved for specific hazard situations. Other somewhat less rigorous approaches are found to provide reasonable estimates of safe separation distances. The most common method relies on identifying minimum or threshold radiation levels that cause ignition or damage. A more sophisticated version of this approach incorporates both the radiation level and a time duration (e.g. flux-time dose).

Various studies have been conducted to measure the threshold levels for radiant ignition of materials [12,13,14]. Some variation exists in the reported results due to differences in the materials, individual test conditions and procedures. However, it appears that the variations are not extreme. For example, the minimum irradiance level for ignition of wood products ranges from 16-30 kW/m^2 [13,15]. Fire retardant treatments of wood products can increase this minimum flux to 40 kW/m^2 [12]. Plastic materials such as polymethylmethacrylate (PMMA) and polyvinyl chloride (PVC) can autoignite at an incident flux exposure of 17-21 kW/m^2 [12]. Certain wire cable insulations can begin to degrade at 12-15 kW/m^2, but typically will not autoignite until the radiant flux levels reach 20-30 kW/m^2.

Estimates of threshold irradiance levels for equipment damage vary considerably. DiNenno [16] recommends a conservative value, around 10 kW/m^2. This level is appropriate when considering exposure of electronic equipment, cables, and so forth. For large pieces of equipment without sensitive electronic components, the greater thermal inertia would permit much higher levels of thermal radiation. Gelderblom [17] suggests a threshold value as high as 35 kW/m^2 for heavy equipment. Table 5 provides a brief summary of threshold values for radiant ignition and equipment damage based on the literature.

Extensive small scale tests have been conducted on selected materials to determine the flux-time dose required for ignition. Fig. 7 provides results of testing for six material types and #2 fuel oil (pool). At high flux levels (e.g. 60 kW/m^2) all of the materials, with the exception of the fire retarded plywood, ignited in less than 20 seconds. As the flux levels are reduced the time required to heat the material to its ignition temperature increases. In the case of each material, some lower limit is reached which represents the threshold or minimum irradiance level for ignition. As discussed above, the value is essentially what is routinely measured and used for evaluating separation distances for common materials.

In order to evaluate the hazard potential to materials and equipment from continuous exposure to an incident flux from a spray fire, a set of criteria was selected. Three ranges of minimum critical radiant flux were established based on review of available estimates of damageability for selected materials (see Table 5).

Table 5 - Damageability Levels for Thermal Radiation

Level	Critical Incident Flux (kW/m^2)	Damageability
I	10-19	. failure of electronic equipment . degradation of thermoplastics, cable insulations
II	20-30	. ignition of wood products . ignition of thermoplastics . ignition of cable insulation
III	> 30	. heavy equipment damage . ignition of fire retardant materials

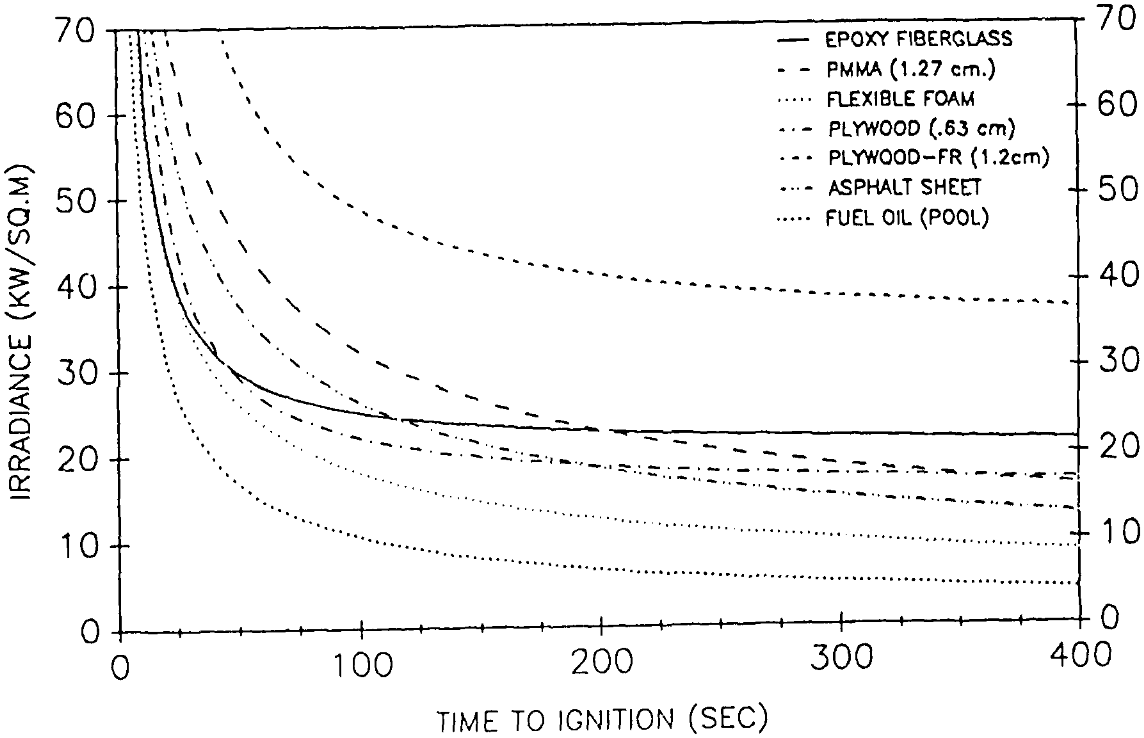

Fig. 7 Radiant Ignition Times for Common Materials [12]

Table 6 provides a simplified tabulation of the damageability levels at distances of 3.0, 6.1, and 9.1 m (10, 20 and 30 ft) from the base of the fire for the sounding tube, petcock and slit pipe scenarios. These results indicate that at least level I damage can be expected at distances up to 6.1 m (20 ft) for any of the three fire cases studied. At a distance of 3.0 m (10 ft), the slit pipe scenario resulted in the lowest irradiance levels of the three fire types but still reached level II damageability. The sounding tube produced irradiance levels at 3.0 m (10 ft) far in excess of the minimum for level III damageability (e.g. >30 kW/m^2). In essence, it would appear that the potential for ignition of materials and equipment damage is quite high for the sounding tube scenario at distances up to 9.1 m (30 ft). The petcock scenario resulted in a somewhat lower intensity fire, but the peak irradiance of 28.3 kW/m^2 was considered close enough to approximate a level 3 condition at 3.0 m (10 ft). (Fig. 6 provides a more detailed estimate of the damageability ranges, indicating that a severe damage potential (i.e., levels II and III) exists for distances up to 4.5 m (15 ft) from the base of the petcock fire.) The slit pipe scenario resulted in a slightly less intense fire than the petcock spray leak, resulting in high damage potential for distances up to 3.0 m (10 ft).

Table 6 - Estimated Damageability Levels

Spray Fire Scenario	Distance From Fire m(ft) 3.0(10)	6.1(20)	9.1(30)
Sounding Tube	III	III	II
Petcock	III*	I	--
Slit Pipe	II	I	--

* Peak irradiance of 28.3 kW/m^2 approached level III.

The results also indicate that the potential for damage to sensitive electronic equipment and cables is quite high for all three fire scenarios. Level I damageability was exceeded at distances beyond 9.1 m (30 ft) in the sounding tube tests, up to 7.0 m (23 ft) in the fully open petcock test, and up to 6.1 m (20 ft) in the slit pipe tests.

It appears that efforts to extinguish these types of spray fires must be introduced rapidly in order to limit the extent of damage. It is difficult to determine how much time is actually available since the analysis is based on attainment of minimum critical irradiance levels, essentially ignoring the time dependence associated with heating a material to its degradation or ignition temperature. Other experimental work indicates that at flux levels associated with level III, serious damage will occur in a matter of seconds. However, at irradiance levels of 10 kW/m^2 (i.e., the lower limit of level I) considerable time may be available to initiate suppression.

Insufficient information is available to conduct a comprehensive analysis incorporating time dependence. However, a limited analysis was performed in which the "time to ignition" was estimated for the materials presented in Fig. 7. While these materials may have limited direct applicability in typical machinery spaces, the necessary detailed laboratory data on radiant ignition exist for each of them in the open literature. The approach would be suitable for evaluating alternative materials and equipment given the basic laboratory data on time-dependent radiant ignition or damage initiation. It also provides a basis for estimating the ignition times for materials having similar properties to those presented in Fig. 7.

The time to radiant ignition of each of the seven materials was determined for each spray fire scenario. An upper limit of 400 seconds was selected as the maximum time of exposure. The ignition times were determined for four horizontal distances from the base of the fire: 3.0, 4.5, 6.1, and 9.1 m (10, 15, 20 and 30 ft). The results are tabulated in Table 7.

The times to ignition can be related directly to an "available" time to initiate suppression. For example, if one minute is needed to deploy manual suppression and effectively reduce thermal radiation below ignition or damage initiation levels, it would appear that this criterion would be satisfactory for the slit pipe scenario. While ignition of the fuel oil spill may occur within one minute if in close proximity to the spray fire [e.g. distance $\leq$ 3.0 m (10 ft)], a considerable margin of safety exists for the remaining six materials.

The one minute delay in effective deployment of suppression is less attractive for the sounding tube and petcock fires. Due to their higher intensities, suppression must be initiated sooner in order to prevent ignition and damage initiation at considerable distances from the fire. In the case of the petcock spray fire, a one minute delay could result in ignition of some materials at a distance of 3.0 m (10 ft), and ignition of the fuel oil spill at 4.5 m (15 ft). For the sounding tube fire, the hazard potential is

Table 7 - Estimated Radiant Ignition Time for Selected Materials

Spray Fire Scenario	Material	Radiant Ignition Threshold (kW/m^2)	Time To Radiant Ignition(s) — Distance, m(ft): 3.0(10)	4.5(15)	6.1(20)	9.1(30,
			Irradiance (kW/m^2): 65.5	50	38	20
Sounding Tube	Fuel Oil	--*	8	10	18	40
	Flex. Polyu. Foam	18	10	17	20	85
	Epoxy Fiberglass	20	10	17	35	200
	PMMA	17	25	45	75	260
	Plywood	16	15	23	30	123
	Fire Retarded Plywood	40	50	95	--	--
	Asphalt Sheet	14	20	30	45	188
			Irradiance (kW/m^2): 28.3	21	13.4	6.3
Petcock	Fuel Oil	--	30	40	130	210
	Flex. Polyu. Foam	18	40	80	--	--
	Epoxy Fiberglass	20	50	155	--	--
	PMMA	17	135	215	--	--
	Plywood	16	65	110	--	--
	Fire Retarded Plywood	40	--	--	--	--
	Asphalt Sheet	14	87	163	383	--

* indicates material would not ignite at that irradiance level over the time period examined (e.g. 400 s)

Table 7 - Estimated Radiant Ignition Time for Selected Materials

(Continued)

Spray Fire Scenario	Material	Radiant Ignition Threshold (kW/m^2)	Time To Radiant Ignition(s)			
			Distance, m(ft)			
			3.0(10)	4.5(15)	6.1(20)	9.1(30)
			Irradiance (kW/m^2)			
			20	13.9	12.6	4.9
Slit Pipe	Fuel Oil	--	45	128	145	300
	Flex. Polyu. Foam	18	85	--	--	--
	Epoxy Fiberglass	20	--	--	--	--
	PMMA	17	260	--	--	--
	Plywood	16	123	--	--	--
	Fire Retarded Plywood	40	--	--	--	--
	Asphalt Sheet	14	179	381	385	--

* indicates material would not ignite at that irradiance level over the time period examined (e.g. 400 s)

extended to 6.1 m (20 ft) for most of the materials, with a potential for igniting a fuel oil spill at 9.1 m (30 ft).

To provide some experimental data on the autoignition of materials by a spray fire, six different materials at two distances from the fire were exposed to the radiant flux. Two plywood test stands were painted black. Material samples, including newsprint, corrugated cardboard, unpainted plywood, standard PVC insulated cable, special PVC insulated cable and crosslinked polypropylene insulated low-smoke producing cable were mounted to the vertical surface of the test stands. The test stands were then placed 3.0 m (10 ft) and 6.1 m (20 ft) from the fire.

When exposed to the high intensity sounding tube fires the newsprint and cardboard on the 3.0 m (10 ft) board autoignited within 30 seconds. Soon thereafter the unpainted plywood ignited. The cable samples did not autoignite but the insulation of the two PVC cables blistered and/or charred. The crosslinked polypropylene low-smoke cable was not damaged to the same degree as the PVC cables; the insulation blistered but did not ignite or char. The materials on the 6.1 m (20 ft) sample board did not ignite during any of the tests but the newsprint and cardboard did char and the PVC cables blistered. The moderate intensity slit pipe fire did not cause autoignition of any of the samples at either distance and only resulted in some charring of the newsprint.

These autoignition experiments were performed to estimate the ignitability of selected samples due to exposure to radiant flux from the spray fire scenarios. It was found that many factors, including wind direction and speed, had a significant influence on the results, and therefore the results are included here for discussion purposes only. The results suggest that a maximum suppression initiation time of 30 seconds is appropriate for fires similar in intensity to the open petcock scenario. But even a 30 second deployment time may not be adequate to prevent radiant ignition and equipment damage for fires such as the sounding tube scenario. Radiant ignition thresholds are reached for various materials at a 6.1 m (20 ft) distance from the fire in less than thirty seconds.

4.2.3.2 Injury/Survivability Hazards

Fuel spray leak fires of the magnitudes studied in this project can pose a serious hazard relative to escape, initial manual fire fighting efforts and reentry. While thermal radiation is only one aspect of the injury and survivability hazard, clearly it is an important and potentially dominant element in the initial stages of a spray leak fire. Only a small fraction of the most serious fire fighter burn injuries are the result of direct flame impingement [18].

Various researchers have studied the effects of thermal radiation on humans. While much of the work has focused on long term effects of relatively low levels of thermal radiation, sufficient work has been done on high radiation effects to provide a basis for evaluating the potential effects of spray fires.

Early work by Stoll and colleagues at the U.S. Naval Air Development Center established important benchmark assessments of critical radiant flux for human injury [19]. Stoll determined that unbearable thermal injury to skin occurred when the radiant flux exposure resulted in threshold blistering. Blistering typically occurs at skin temperatures at or above 45°C [18,19]. At skin temperatures above 72°C, irreversible and instantaneous necrosis of human skin occurs [20].

A study with humans having their forearms exposed over a range of thermal irradiances [19] demonstrated that thermal radiation intensities as low as 4.2 kW/m^2 can produce threshold blisters in just 34 seconds. Extrapolation of this test data [20] suggests a minimum of 3 kW/m^2 for exposure times greater than one minute. Parker and West [21] report an asymptotic minimum flux of 2.4 kW/m^2 for pain, below which the heat energy is carried away by the blood supply at a rate which maintains the skin surface temperature below the pain threshold. At flux levels of 2.4 kW/m^2 and 3 kW/m^2 respectively, pain and blistering thresholds are exceeded in about one minute.

Stoll and Chianta [22] developed "dose" relationships for both pain and second degree burns which account for the irradiance level and the duration of exposure. The dose or exposure curves presented in Fig. 8 are based on their work. The pain threshold criterion is selected here to provide some estimate of a lower limit in terms of the onset of injury conditions. The second degree burn criterion is an accepted criterion in the burn injury research community as a critical injury point. Second degree burns result in deep tissue damage to the base of the skin layer [23]. If this occurs over large surface areas, extensive medical treatment will be required. Burn injuries more severe than this result in extreme difficulties in healing and frequently such burn injuries result in death.

Other researchers have selected minimum or threshold values for critical radiant flux as a single point injury criterion. Veghte [24] reported that Uteck, in research directed at development of fire fighter protective clothing,

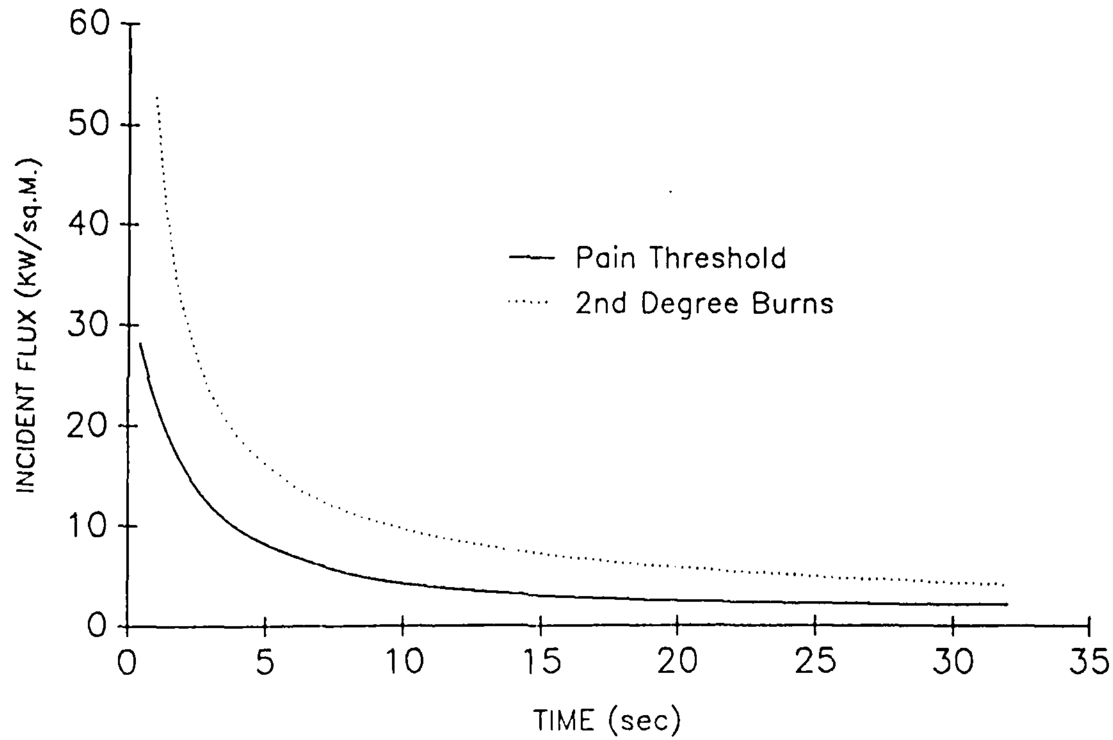

Fig. 8 Minimum Incident Flux—Time for Unprotected Skin [22]

identified a critical level of 12.3 kW/m^2 to represent a minimum flux level that protective clothing must resist for emergency conditions. Both Uteck and Babrauskas [15] suggested an exposure flux of 2.5 kW/m^2 as the maximum level for exposure to the skin surface. Parker and West [21] reported a somewhat higher value of 3.4 kW/m^2.

The flux-dose criteria presented in Fig. 8 for pain and second degree burns were used in evaluating the potential thermal radiation hazard to unprotected occupants exposed to the three spray fire scenarios of interest in this study. The pain threshold criterion is felt to be somewhat conservative, and was selected to represent a signal or warning point regarding injury potential. The second degree burn criterion was selected as a critical criterion for fire fighting and escape - the point at which serious injuries or fatalities may result from continued exposure. It should be emphasized that for purposes of this part of the analysis, it was assumed that individuals would not be wearing protective clothing, and that portions of the body would be exposed (e.g. arms, hands, face, neck). These areas, typically not covered, are also some of the most susceptible areas of the body to burn injury [21].

Not surprising, the spray fire scenarios tested in this series (e.g. uncapped sounding tube, open petcock and slit pipe) resulted in thermal radiation levels well in excess of levels required to exceed pain or second degree burn thresholds over very short time periods. For example, the slit pipe spray fire resulted in an average peak irradiance of 4.9 kW/m^2 at a distance of 9.1 m (30 ft). Under these conditions, the pain threshold would be exceeded in less than ten seconds. In addition, this flux level of 4.9 kW/m^2 was the lowest level measured (see Table 4), indicating that the pain threshold would be exceeded in close proximity to a spray leak fire very quickly for the other cases studied here. Table 8a provides a summary of the times to reach the pain threshold at distances of 3.0, 6.1, and 9.1 m (10, 20 and 30 ft) from the fire for each of the spray fire scenarios evaluated.

Table 8a - Approximate Time to Reach Pain Threshold (s) (Unprotected Skin)

Spray Fire Scenario	Distance From Fire, m(ft) 3.0(10)	6.1(20)	9.1(30)
Sounding Tube	*	*	<2
Petcock	<1	2.5	6
Slit Pipe	<2	2	8

* Indicates Threshold Exceeded Instantaneously

Table 8b provides similar data for the second degree burn threshold. As expected, the elapsed times are somewhat greater than those associated with the pain threshold. However, the time ranges are still relatively short, indicating that little time is available to respond to the fire incident before serious injury conditions exist if the personnel are unprotected. Fig. 9 illustrates this graphically. If, for instance, a ten second endurance is needed, the individual must be at least 7.6 m (25 ft) from the slit pipe or petcock fire to avoid flux-time doses that exceed the second degree burn threshold. For an individual stationed 6.1 m (20 ft) from the fire, the available time is under ten seconds for any of the spray fires tested.

Table 8b - Approximate Time to Reach Second Degree Burn Threshold - Unprotected Skin (s)

Spray Fire Scenario	Distance From Fire, m(ft) 3.0(10)	6.1(20)	9.1(30)
Sounding Tube	*	<2	3
Petcock	2.5	6	20
Slit Pipe	3	7	24

* Indicates Threshold Exceeded Instantaneously

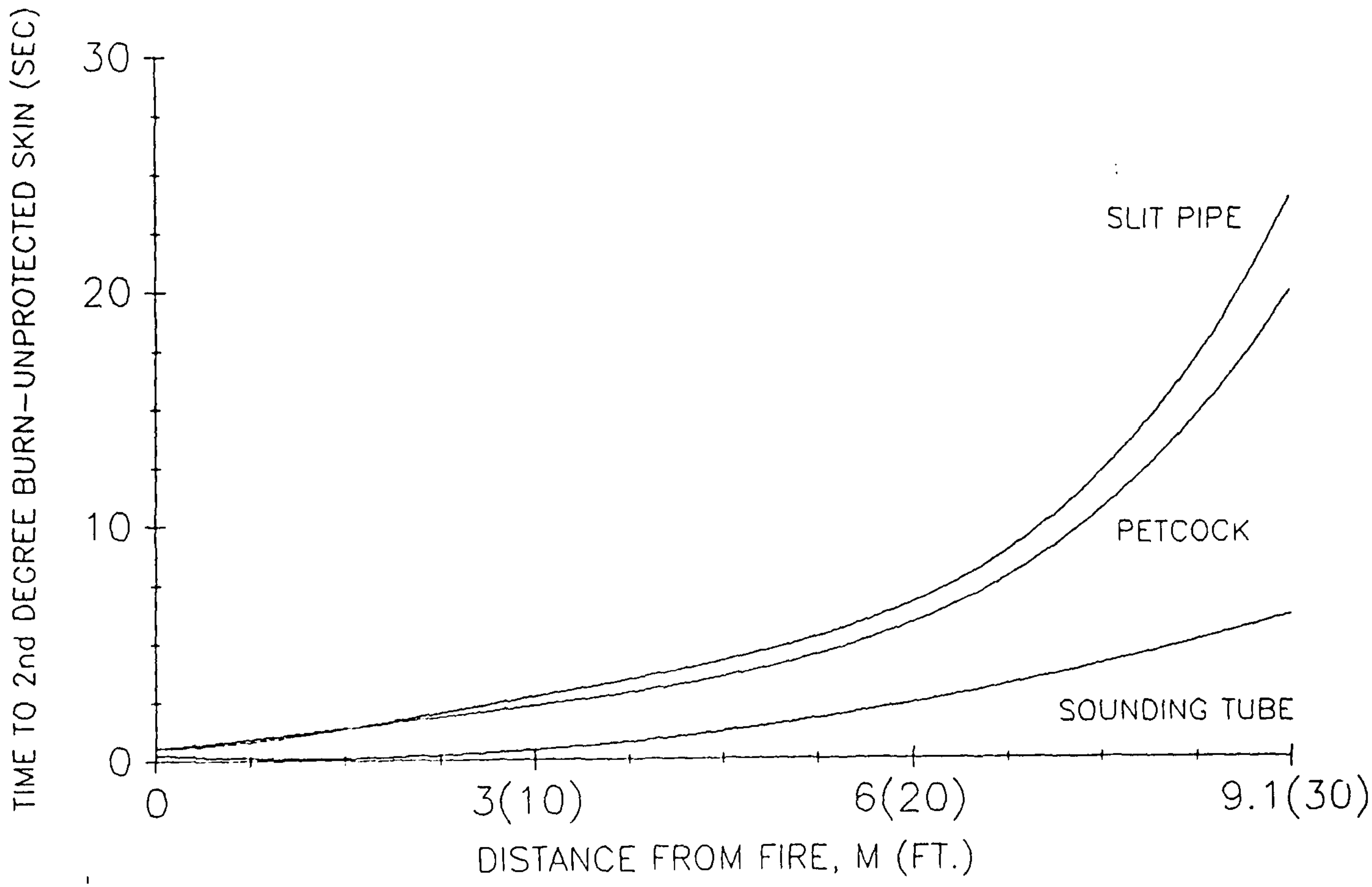

Fig. 9 Time to Second Degree Burn Threshold for Different Spray Fires and Separation Distances

The results of this analysis indicate that typical fuel spray leak fires pose serious injury and survivability hazards. If individuals are stationed in the proximity of such fires and have unprotected skin surfaces, the time available for escape or to significantly reduce the fire intensity is only a matter of seconds. In the case of a severe exposure such as that from a sounding tube spray fire, even at 9.1 m (30 ft) away from the fire, serious injuries can be sustained in as little as five seconds.

If an individual has protective clothing such as a Nomex garment (or a material of similar insulative properties) and protection for his face and hands, the available time to react can be increased significantly. Fig. 10 illustrates this effect for a relatively high incident flux level of 41 kW/m^2. If an endurance time of twenty seconds is desirable for an exposure level of 41 kW/m^2, the insulative characteristics of a 37 mil [0.94 mm (0.037 in.)] thickness Nomex garment material is required. While twenty seconds may not be an adequate endurance time for many situations, it represents an attainable enclosure evacuation time. In addition, for fires of the intensities characterized by the petcock and slit pipe scenarios, protected individuals may, in some cases, be able to commence suppression. If the suppression method is effective in reducing the thermal radiation, the injury and survivability hazard will subsequently be reduced. This aspect of the problem is examined in Section 4.3.

4.2.3.3 Predicted Enclosure Effects

Thermal radiation due to flame geometry does not fully represent the hazard associated with fuel leak spray fires in machinery spaces. Other related factors include oxygen depletion, carbon monoxide production and smoke particulate generation. However, the impact of these factors on machinery space environments can not be readily determined from the experiments conducted in this series, since these effects are directly influenced by enclosure geometry and ventilation conditions.

As discussed in Section 2.2, Kay [4] observed substantial smoke production in large scale machinery space spray fire tests, dramatically affecting visibility in 30 to 45 seconds. He also reported ventilation controlled burning, resulting in high carbon monoxide (CO) generation rates in a matter of seconds. DiNenno [1] reported similar results for spray fires conducted in 1986 as part of a broader study of machinery space ventilation effects. Critical limits for smoke obscuration were exceeded in 30 to 85 seconds, depending on the initial burning rate and the ventilation

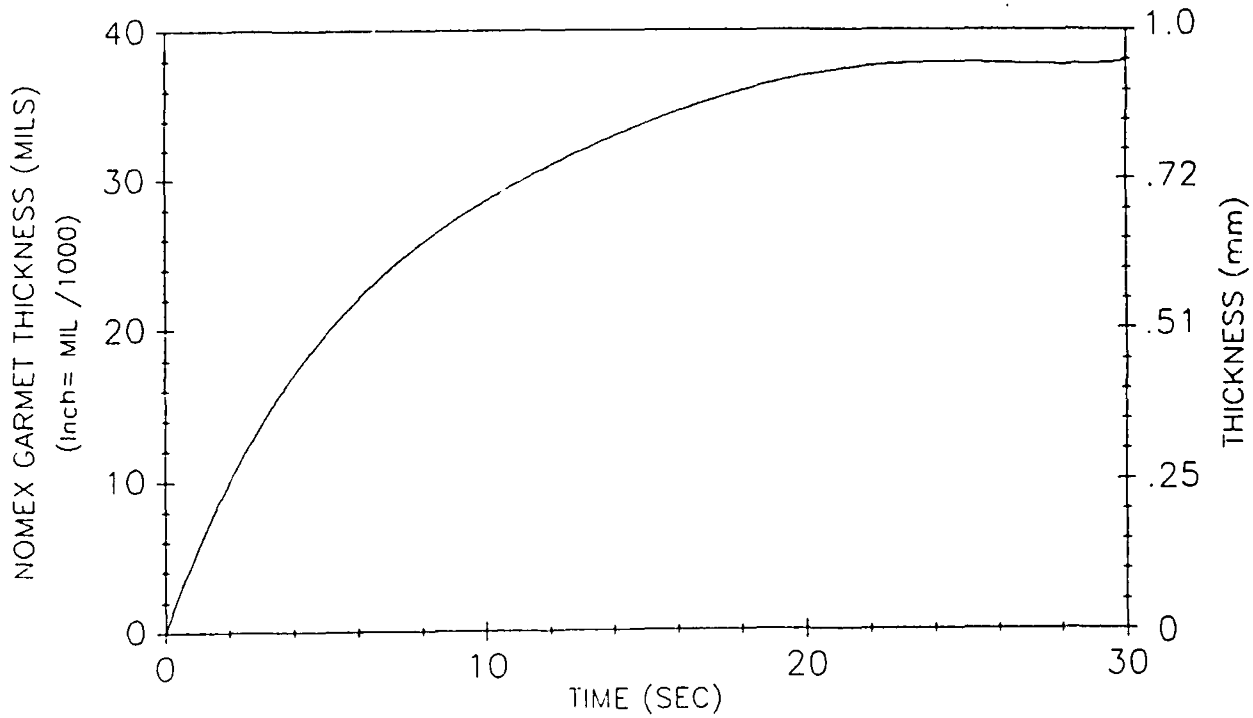

Fig. 10 Time to Second Degree Burns at Critical Incident Flux of 41 KW/sq.M

conditions. Untenable CO levels were reached in two to three minutes.

Since the enclosure and ventilation conditions can dramatically affect hazard conditions resulting from typical fuel spray fire incidents, an attempt was made to approximate such affects using a modified version of the Harvard Computer Fire Code V [25].

This computer based enclosure fire growth model requires that data be provided on the size and geometry of the compartment, ventilation conditions and fire size and growth rate. It treats the enclosure fire as a series of control volume problems, a typical approach to enclosure fire approximations.

To simulate a typical large machinery space that would be found on an aircraft carrier or other large vessel, an area 9.1 m (30 ft) by 9.1 m (30 ft) with an overhead height of 9.1 m (30 ft) was considered. Three different fire sizes were used: 30, 15 and 5 MW. These were considered to represent a lower range of heat release rates from the different spray fire scenarios tested.

Realizing that the effect of ventilation on a fire in any compartment is significant, five different representative ventilation conditions were simulated. These included:

(1) high supply,
(2) high exhaust,
(3) no vents,
(4) a single open hatch and
(5) a condition of simultaneous high supply and exhaust. High in these cases is 6.17 cubic meters per second (13,000 cfm).

The results of the computer runs are presented in Table 9. Two criteria were used to evaluate the impact of a hot layer formed in the enclosure due to a burning spray fire. The first criterion considered was the time required for the hot gas layer to descend to a height of 1.5 m (5 ft) above the deck (eye level). Table 9 shows the time required for the layer to drop to eye level and the temperature of the layer at that time. This was considered a critical threshold for exposure of personnel to hazardous conditions which would significantly inhibit manual fire fighting and escape.

The results show that for all cases the time for the layer to drop to eye level was less than 60 seconds. When there were no vents or only an opened hatch (i.e., case 3 and 4) the time for layer descent to the 1.5 m (5 ft) level was calculated to be extremely short, on the order of 11 seconds.

TABLE 9. PREDICTED ENCLOSURE AND VENTILATION EFFECTS

30X30X30 FT. MACHINE SPACE SIMULATION

TIME (SEC) FOR LAYER TO DROP TO EYE LEVEL [1.5 m (5 FT) ABOVE FLOOR]

		FIRE SIZE		
CASE NO.	VENTING	30 MW	15 MW	5 MW
1	SUPPLY HIGH	20	26	38
2	EXHAUST HIGH	28	60	*
3	NO VENTS	11	15	26
4	OPEN HATCH	11	16	30
5	EXH & SUP HIGH	11	15	31

* STEADY AT 2.1 m (7 ft) AFTER 60 sec.

LAYER TEMPERATURE (C) WHEN LAYER IS AT EYE LEVEL

		FIRE SIZE		
CASE NO.	VENTING	30 MW	15 MW	5 MW
1	SUPPLY HIGH	585	372	156
2	EXHAUST HIGH	627	420	173
3	NO VENTS	468	312	138
4	OPEN HATCH	478	312	145
5	EXH & SUP HIGH	471	312	149

TIME (SEC) FOR LAYER TO REACH 502 C

		FIRE SIZE			
CASE NO.	VENTING	30 MW	15 MW	5 MW	
1	SUPPLY HIGH	7	**	>200	
2	EXHAUST HIGH	5	**	>200	
3	NO VENTS	(468 MAX)	(334 MAX)	(164 MAX)	All Oxygen Starvation
4	OPEN HATCH	(484 MAX)	(350 MAX)	(226 MAX)	All Oxygen Starvation
5	EXH & SUP HIGH	(471 MAX)	(341 MAX)	>200	1&2 Oxygen Starvation

** 440 C AT 200 SEC.

The second criterion in evaluating the hazard was the layer temperature. Once the hot gas layer reaches a temperature on the order of 502°C (935°F), it is capable of radiating that heat to the rest of the compartment at a flux approaching 20 kW/m^2. This radiant flux level is capable of causing auto-ignition of combustible materials in the room, damage to electronic equipment and electrical cables (see Table 10) and producing a condition commonly referred to as flashover. At this point there is no question that the space is untenable, and extensive damage to equipment and electronics can be expected.

The results show that, depending on the ventilation condition, two outcomes are possible. In the case of the 30 and 15 MW fires where the ventilation rates were high (i.e., cases 1 and 2), the layer temperatures climbed rapidly and reached the threshold for flashover in less than 10 seconds. When the ventilation rates were not high (i.e., cases 3 and 4) the fires became ventilation controlled, could not burn at the maximum heat release rate and the layer temperature tended to peak at some value and then begin to decrease. Here again the atmosphere would be hazardous because of the high temperature, toxic gases and the reduced oxygen.

Table 10 - Minimum Irradiance Levels For Ignition of Materials and Equipment Damage

ITEM	MINIMUM IRRADIANCE (kW/m^2)
Electronic Equipment	10 (damage)
Thermoplastics	15 (degradation)
	20 (ignition)
Cable Insulation	20
Wood Products	20
Heavy Equipment	35 (damage)
Fire Retarded Wood	40

It is important to remember, when considering the results of this analysis, that the computer model has been used at the upper limit of its prediction capacity. This is due to our limited understanding of high momentum driven fire sources and the associated high rates of heat release within the enclosure. This analysis was conducted to determine the relative levels of hazard under these conditions. The values should be considered crude estimates; full scale testing is needed to generate a precise accounting of the layer dynamics, factors which play an important role in development of hazardous conditions.

4.3 Phase II - Suppression Tests

4.3.1 Suppression Quantification

Characterization of the three spray fire scenarios (e.g. sounding tube, petcock and slit pipe) was done in Phase I to quantify the hazard impact of these fires. The sounding tube was evaluated as a high hazard fire which would present a high challenge for suppression based on its magnitude alone. The petcock and slit pipe fires were evaluated as moderate hazard fires. Since the petcock was tested with a vertical spray, it presented a scaled down version of the sounding tube, the suppression of which would be similar to the sounding tube except that the challenge would be somewhat less. The slit pipe, however, was directed at the debris pile which introduced a shielding effect. This shielding presents a greater challenge to suppression.

It was desirable to examine both high and moderate intensity fires as well as shielding effects in the suppression tests. Therefore, the sounding tube in a vertical orientation and the slit pipe sprayed at an angle into the debris pile were selected for testing in Phase II. A continuous ignition source was utilized for all of the suppression cases because of the greater consistency and stability of the spray jet fire.

Two criteria were used to evaluate suppression effectiveness: visual evidence of suppression and reduction in radiant flux. Test observations and video cameras were used for the former and radiometer data for the latter. Temperature data were also collected at various points but analysis of these data indicated many inconsistencies which were attributed to wind effects, suppression agent interference and/or fire induced convective currents. No quantifiable suppression effects or trends could be deduced from the temperature data an for this reason were not used.

Table 11 summarizes all of the suppression tests, including the agents used, application method and conditions at the time of the tests. Also indicated is whether or not the resultant pool fire and spray jet fire were visually observed to be extinguished. Figures 11-17 show application of various agents during the tests.

Generally the pool fire resulting from the sounding tube scenario was easily extinguished by AFFF and/or PKP. However, the only agent and application method which was observed to extinguish the sounding tube jet fire was the 95 gpm AFFF hand line. The slit pipe scenario did not produce a pool fire in the vicinity of the fuel discharge.

TABLE 11 PHASE II SPRAY FIRE SUPPRESSION TESTS

TEST NO.	GEOMETRY	IGNITION	FUEL FLOW RATE	AMB TEMP	WIND	EXT. AGENT	APP. MODE	EXT.POOL Y/N TIME, Sec	EXT. SPRAY Y/N TIME, Sec
SFS 001	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	1.6 C 35 F	2-4 KN NE-SW	AFFF	TAFES- AFFF ONLY	Y, 22	N
SFS 002	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	1.6 C 35 F	2-4 KN NE	AFFF, PKP	TAFES	Y, 25	N
SFS 003	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	4 C 40 F	2-4 KN NE-SW	AFFF, PKP	TAFES- AFFF ONLY PKP- 27# PORTABLE	Y, 9	N
SFS 004	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	5 C 41 F	2-4 KN NE-SW	PKP	27# PORTABLE	Y, 9	N
SFS 005	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	2 C 36 F	2-4 KN NE-SW	AFFF	TAFES- AFFF ONLY	Y, 12	N
SFS 006	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	2 C 36 F	2-4 KN NE-SW	AFFF, PKP	TAFES	Y, 9	PARTIAL T+1:45
SFS 007	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	2 C 36 F	2-4 KN NE-SW	AFFF, PKP	TAFES- AFFF ONLY PKP- 27# PORTABLE	Y, 10	?
SFS 008	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	2 C 36 F	2-4 KN NE-SW	PKP	27# PORTABLE	NO POOL FIRE	N
SFS 009	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	12 C 54 F	5-7 KN N	AFFF	95 GPM HANDLINE		Y, 81
SFS 010	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	12 C 54 F	5-7 KN N	AFFF	95 GPM HANDLINE		Y, 105
SFS 011	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	13 C 56 F	5-7 KN N	PKP	2-27# PORT PARALLEL	N	N
SFS 012	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	13 C 56 F	5-7 KN N	Halon 1211	2 PORT IN PARALLEL	N	N
SFS 013	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	13 C 56 F	5-7 KN N	Halon 1211	HANDLINE	N	N
SFS 014	SOUNDING TUBE	CONTINUOUS	155 l/min 41 GPM	13 C 56 F	1-3 KN N	AFFF, PKP	95 GPM HANDLINE 27# PORTABLE	?	Y, 58
SFS 015	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	13 C 56 F	0-3 KN E	AFFF	95 GPM HOSELINE	?	Y, 42
SFS 016	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	13 C 56 F	0-3 KN E	AFFF	95 GPM HOSELINE	?	Y, 1:25
SFS 017	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	13 C 56 F	0-3 KN E	PKP	2 PORT IN PARALLEL	?	Y, 1:08
SFS 018	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	13 C 56 F	3-5 KN E	HALON 1211	HANDLINE	?	Y, 1:31
SFS 019	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	13 C 56 F	3-5 KN E	AFFF, PKP	95 GPM HANDLINE 27# PORTABLE	Y, 1:20	Y
SFS 020	SLIT PIPE, 45	CONTINUOUS	20.8 l/min 5.5 GPM	13 C 56 F	3-5 KN E	HALON 1211	2 PORT IN PARALLEL	N	N

TABLE 11 (CONTINUED)

NO.	NOTES
SFS 001	FIRE BURNED ON OBSTRUCTIONS UNTIL FUEL WAS SECURED APPLIED AFFF FOR 2 MINUTES
SFS 002	PREBURN 30 SEC, 2 SEC BURSTS OF PKP, PKP APPLIED UNTIL EXPENDED, AFFF APPLIED FOR 2 MIN, FIRE WAS NOT SUPPRESSED
SFS 003	PREBURN 30 SEC, PKP DISCHARGED DIRECTLY TO BASE OF SPRAY; FIRE DECREASED IN INTENSITY, FIRE CONTINUED TO BURN ON OBSTRUCTIONS
SFS 004	POOL FIRE SUPPRESSED BUT REIGNITED AT 17 SEC WHEN PKP WAS DEPLETED
SFS 005	FIRE WAS NOT COMPLETELY EXTINGUISHED BECAUSE OF SHIELDING/BLOCKAGE BY DEBRIS PILE
SFS 006	DEBRIS PILE PREVENTED COMPLETE SUPPRESSION
SFS 007	FIRE SUPPRESSED, PKP HANDLED SHIELDED BURNING, VISIBILITY CONSIDERABLY REDUCED BY PKP CLOUD
SFS 008	BURNING CONTINUED ABOVE AND BELOW DEBRIS PILE ROOF
SFS 009	OVERHEAD SERVED AS FLAME HOLDER UP TO 30 SEC AFTER START
SFS 010	REPEAT OF SFS009
SFS 011	AGENT HAD NO APPARENT EFFECT, 30 SEC PREBURN
SFS 012	AGENT HAD NO APPARENT EFFECT, 30 SEC PREBURN
SFS 013	AGENT HAD NO APPARENT EFFECT, 30 SEC PREBURN
SFS 014	AFFF SUPPRESSED AND PKP PORTABLE EXTINGUISHED REMAINING FLAMES ON OBSTRUCTIONS AND DEBRIS PILE
SFS 015	30 SEC PREBURN, EXTINGUISHED 12 SEC AFTER AGENT APPLICATION
SFS 016	FIRE EXTINGUISHED 12 SEC AFTER AGENT APPLICATION
SFS 017	EXTINGUISHED 8 SEC AFTER AGENT APPLICATION, REIGNITED 15 SEC AFTER EXTINGUISHMENT (7 SEC AFTER AGENT EXPENDED)
SFS 018	EXTINGUISHED 8 SEC AFTER AGENT APPLICATION, REIGNITED 32 SEC AFTER EXTINGUISHMENT (19 SEC AFTER AGENT EXPENDED)
SFS 019	AFFF USED TO ATTACK DEBRIS PILE, PKP USED ON POOL FIRE, BOTH WERE EXTINGUISHED
SFS 020	DEBRIS PILE CONTINUED TO BURN, JET OUT AT 1:33, REIGNITED AT 1:50

Fig.11 Photograph of the application of AFFF via TAFES on sounding tube fire

Fig.12 Photograph of the application of AFFF and PKP via TAFES on sounding tube fire

Fig.13 Photograph of the application of AFFF via TAFES and PKP via portable extinguisher on sounding tube fire

Fig.14 Photograph of the application of AFFF via TAFES on slit pipe fire

Fig.15 Photograph of the application of AFFF and PKP via TAFES on slit pipe fire

Fig.16 Photograph of the application of AFFF via TAFES and PKP via portable extinguisher on slit pipe fire

Fig.17 Photograph of the application of PKP via portable extinguisher on slit pipe fire

In these fires fuel burned in and around the debris pile which obstructed agent application. The spray jet fire produced by the slit pipe was typically extinguished with AFFF alone or in combination with PKP, compared to the sounding tube.

4.3.2 Suppression Results

The greatest challenge presented to the suppression of spray fires is overcoming the thermal radiation. The results from Phase I demonstrate that the very high radiant flux levels produced by these fires quickly renders the space untenable and makes suppression of the fire very difficult.

Radiant flux levels were measured at various locations for all of the suppression tests. These data are provided in Appendix C as plots of radiant flux in kW/m^2 versus time. Since there was some degree of noise and scatter in the data, the flux values were averaged over a quasi-steady period. These periods existed before application of agent in all cases and ranged from approximately 30 to 80 seconds. When the fire was suppressed a second quasi-steady period at a substantially lower radiant flux existed. The average radiant flux before and after agent application are shown in Table 12 for the different suppression methods. The change in the radiant flux due to agent application has also been calculated and included in Table 12.

For a high intensity fire (i.e. sounding tube) the greatest reduction in the flux level resulted from the application of AFFF. The TAFES unit, the 95 gpm AFFF hand line, and the AFFF hand line in conjunction with a PKP portable extinguisher all resulted in significant reductions in radiant flux. Methods which resulted in essentially no flux level reduction included a single 27 lb PKP extinguisher, two 27 lb PKP extinguishers used simultaneously, and Halon 1211 from a portable extinguisher or hand line. Evaluation of the TAFES indicated that the maximum reduction in radiant flux was achieved with this unit when AFFF and PKP (by TAFES or portable) were applied simultaneously. It was observed that the tactics used by the fire fighters were also very important in the effectiveness. The AFFF agent was applied initially to reduce the flame size and radiation, permitting the fire fighters to approach the base of the fire. At this point the AFFF and PKP were applied simultaneously. It appeared that in order to suppress the high intensity sounding tube fire, both the cooling and vapor sealing effects of AFFF and the flame knockdown ability of PKP were needed.

TABLE 12. SUPPRESSION RESULTS- RADIANT FLUX REDUCTION AT 3.1 m (10 FT) DISTANCE

HIGH INTENSITY FIRE- SOUNDING TUBE

	AGENT	PRE-AGENT APPL. MEAN FLUX KW/SQ.M	POST-AGENT APPL. MEAN FLUX KW/SQ.M	FLUX REDUCTION (%)
1	NONE	25.64	25.64	0
2	TAFES-AFFF	25.69	9.16	64.3
3	TAFES-AFFF, PKP	24.60	1.40	94.3
4	TAFES-AFFF, PKP PORT	20.86	3.43	83.5
5	PKP PORT.	22.21	22.21	0
6	95 GPM AFFF	31.00	2.15	93.0
7	95 GPM AFFF,PKP PORT	24.30	0.41	96.8
8	2 PKP PORT PARALLEL	23.60	23.60	0
9	HALON 1211 HANDLINE	24.87	24.87	0
10	HALON 1211 PORTABLE	33.65	33.65	0

MODERATE INTENSITY FIRE- SLIT PIPE

	AGENT	PRE-AGENT APPL. MEAN FLUX KW/SQ.M	POST-AGENT APPL. MEAN FLUX KW/SQ.M	FLUX REDUCTION (%)
1	NONE	3.77	3.77	0
2	TAFES-AFFF	2.91	0.53	81.8
3	TAFES-AFFF, PKP	2.70	0.20	92.6
4	TAFES-AFFF, PKP PORT	4.26	0.18	95.7
5	PKP PORT.	3.43	3.43	0
6	95 GPM AFFF	3.28	0.20	94.0
7	95 GPM AFFF,PKP PORT	7.14	0.28	96.0
8	2 PKP PORT PARALLEL	3.42	0.51	85.0
9	HALON 1211 HANDLINE	4.29	0.26	93.9
10	HALON 1211 PORTABLE	2.48	2.48	0

For a moderate intensity fire with significant shielding (i.e. slit pipe) the greatest reduction in the flux levels again resulted from application of the TAFES unit, the 95 gpm AFFF hand line, and the hand line in conjunction with a 27 lb PKP portable extinguisher. PKP and Halon 1211 were more effective on the slit pipe scenario than the sounding tube. This was attributed to the effects of the gaseous Halon or suspended PKP cloud in overcoming the suppression shielding of the obstructions and reaching the fire burning in the debris pile. However, without AFFF they did not provide any cooling to the hot metal surfaces, which in some cases resulted in reignition of the fuel spray.

As with the sounding tube tests, the TAFES demonstrated improved suppression ability when both AFFF and PKP (by TAFES or portable) were applied simultaneously. A single PKP or Halon 1211 extinguisher had no appreciable effect on the radiant flux or the fire size when used alone. However, a significant reduction in radiant flux was observed for tests using two PKP portable extinguishers simultaneously and for the Halon 1211 hand line.

4.3.3 Analysis of Suppression Effects

The reduced thermal radiation achieved by the application of a suppression agent is an important benefit in controlling spray fuel fires in enclosures. Prior to the application of agent, the flux levels from spray fires such as those tested in this series would make the space untenable, cause material and equipment damage and result in auto-ignition of combustibles within the space. Discounting enclosure effects, the experiments have shown that the flux levels can be reduced significantly, depending on the suppression method selected, potentially permitting fire fighters to approach and extinguish the remaining spray fire either by continued agent application or by securing the fuel. These results are shown in Table 12. At the low flux levels indicated in these tests, the hazard of further damage, ignition of combustibles, or injury to individuals is reduced considerably.

The only agent which was found to be capable of consistently reducing the flux levels to the point where the space became tenable, was AFFF. None of the other agents had the cooling capability of AFFF or were able to absorb the thermal radiation and rapidly reduce the flame size. A drawback of AFFF is that it was not always able to completely suppress or extinguish the fire, especially if the fire was shielded by equipment, piping etc. For this, PKP demonstrated an ability to reach the shielded fire and suppress it, once the dominant spray fire was reduced in intensity.

Once the fire has been suppressed the problem of reignition remains. It was determined that unless the area surrounding the fuel spray is substantially cooled, (i.e., cooled below the spontaneous ignition temperature of the impacting spray), reignition will occur. The only agent which would achieve this was AFFF; PKP and Halon 1211 provided no appreciable cooling ability in the face of a 30 MW spray fire. Of course, securing the fuel will alleviate the reignition problem but that is not always immediately possible in a shipboard fire situation. Until such time that the fuel spray leak can be secured, the results of the tests in Phase II indicate that significant cooling of the flame zone and heated surfaces must be maintained.

5. DISCUSSION

Current shipboard machinery space fire fighting doctrine is intended to assure protection of both personnel and equipment for a wide range of typical fire scenarios. However, the results of this study indicate that manual fire fighting procedures incorporated in the current doctrine may be of limited value in controlling some fuel spray fires. Tests indicate that:

(1) typical leaking fuel sprays can result in considerably more intense fires than expected,
(2) the fires grow rapidly, reaching a quasi-steady maximum size in a matter of seconds, and
(3) readily available obstructions can enhance burning, provide shielding from suppression agents and provide multiple sources for reignition.

An immediate effect of typical fuel spray fires is high near-field thermal radiation. Actual flux levels depend on the spray leak geometry, fuel flow rate and pressure, the enclosure geometry and ventilation. Levels of radiant flux were reached in this test series that would result in damage to electronics and machinery space equipment, ignition of combustibles and burn injuries to unprotected personnel in relatively short time periods. In the case of the high intensity fire resulting from the simulation of an uncapped sounding tube spray leak, damage and burn injuries could occur 6.1-9.1 m (20-30 ft) away from the fire source in less than 10 seconds.

Moderate intensity spray fires such as those selected to simulate the open petcock and the slit pipe were less severe, providing somewhat more time to react before critical thresholds for injury and damage were exceeded.

While testing did not include examination of enclosure effects, calculated estimates indicate that untenable conditions will be reached in a typical machinery space enclosure, perhaps in a matter of seconds, due to high temperatures and high concentrations of carbon monoxide and smoke, all developing in a relatively short period of time.

Suppression of the spray fires tested in this series appeared to occur in two stages: namely, reduction of thermal radiation followed by flame suppression. Disregarding the inherent time delay associated with deployment of manual fire suppression, various methods were capable of significantly reducing the thermal radiation once agent application was initiated. This was generally accomplished through flame zone cooling with AFFF. Similar results could not be achieved with PKP or Halon 1211.

Once the fire size was substantially reduced, complete extinguishment depended on the flame geometry, burning rate, and shielding effects from obstructions and simulated equipment. In the case of the high intensity fire from the uncapped sounding tube, complete extinguishment was not achievable with any of the methods tested. However, the fire burned at a significantly reduced rate and the hazard due to thermal radiation was very small while AFFF was applied to the fire.

Extinguishment of the moderate intensity slit pipe fire was accomplished by directing PKP agent at the base of the spray and in the direction of any obstructions. Once the AFFF, which was applied simultaneously, had reduced the thermal radiation sufficiently, personnel were able to approach the base of the fire and initiate final suppression with the PKP which was entrained directly by the fuel spray and carried into the shielded or obstructed areas.

Several suppression methods performed satisfactorily (i.e., produced a substantial reduction in thermal radiation or complete extinguishment), including the TAFES unit, the 95 gpm AFFF hand line and the hand line in conjunction with a PKP portable extinguisher. Suppression was achieved in two stages, as described above. The TAFES unit performed satisfactorily, but not as well as the 95 gpm AFFF hand line in combination with a portable PKP extinguisher. The improved effectiveness of the hand line/portable PKP combination was due to: (1) the increased flow rate of AFFF (95 gpm for the hand line vs 60 gpm for the AFFF side of the TAFES) and (2) to the greater maneuverability of the portable extinguisher as opposed to the PKP side of the TAFES which is shackled to the AFFF nozzle. Observations during the tests indicate that for the high intensity fires, an agent-reach problem existed with the AFFF side of the TAFES unit, limiting its effectiveness in reducing the thermal radiation. In addition, no qualitative difference in suppression was observed when substituting a 27 lb PKP portable for the PKP side of the TAFES unit. Limited effectiveness was observed when either PKP or Halon 1211 was used without simultaneous application of AFFF, further demonstrating the need for rapid, effective flame cooling.

While the results of these tests are encouraging regarding the control of fuel spray fires, additional issues have been identified which directly affect machinery space fire fighting and reentry guidelines for fuel spray fires.

For example, typical spray fires may exceed the capabilities of current manual fire fighting techniques. In addition, environmental conditions may deteriorate so rapidly that the only feasible manual methods are those that can be deployed very quickly (in seconds). Further complications include the potential rapid spread of the spray fire to combustible materials in the machinery space, and the problem of reignition due to heated surfaces. Of particular concern is the effectiveness of total flooding suppression systems such as Halon 1301 on burning fuels, deep seated burning of Class A combustibles, cables and electronic equipment, and cooling of hot surfaces. These effects directly influence consideration for reentry procedures as well as operational integrity.

Further testing and analysis are necessary to verify the effects of spray fires and methods of extinguishment. A major limitation of the tests conducted so far is the absence of any enclosure effects. To accurately assess fire hazard development due to fuel spray fires and the impact of suppression candidates, tests should be performed in an enclosure which at least simulates the geometric and ventilation conditions expected in a machinery space. Such tests could provide quantitative data relative to survivability and damageability, the feasibility of manual fire fighting, the effectiveness of manual and fixed total flooding suppression methods, and hazards associated with reentry procedures.

Conceivably, the results of such tests would lead to selection of appropriate optimum suppression procedures, criteria for maximum fire size for manual fire fighting, an assessment of the potential effectiveness of current procedures and identification of necessary modifications to current machinery space fire fighting procedures. The results may also indicate the need for additional measures for protection of machinery spaces and personnel from fuel spray fires. Candidate measures for consideration include:

(1) increased inspection and fire prevention training,
(2) revised training procedures,

(3) control of ignition sources,
(4) fuel leak detection and alarm,
(5) remote fuel shut-off, and
(6) alternative suppression methods.

6. SUMMARY AND CONCLUSIONS

Summary:

The primary objectives of this study were to:

(1) characterize typical/representative fuel spray fires, and
(2) evaluate the impact of the PKP side of the TAFES unit in suppressing these fires.

An additional objective was to determine the feasibility of suppression or control of such fires by selected suppression methods that could be made available for shipboard fire fighting. In all, nine suppression options were evaluated against two well characterized fuel spray fires. One fire simulated an uncapped sounding tube spray fire; the other simulated a damaged or fractured pipe or pipe joint. These two spray fire scenarios provided significantly different burning rates and geometry effects.

Large scale test results indicate that typical fuel spray fires such as those simulated in this series are very severe. Flame heights ranged from 6.1 m (20 ft) for the slit pipe to 15.2 m (50 ft) for the sounding tube scenario. These large flame geometries were accompanied by heat release rates of 6 MW to greater than 50 MW, and hazardous thermal radiation levels in the near-field environment, up to 9.1 m (30 ft) away. If unsuppressed, fires of these magnitudes could result in damage to electronics and machinery equipment, ignition of combustibles, and severe burn injuries to personnel located in the machinery space in just a few seconds The actual time to hazardous conditions would depend on the arrangement of equipment and materials, the location of the personnel, and the enclosure and ventilation effects.

These spray fires were characterized predominantly by high flame radiation and shielded burning. Successful suppression of these fires required both a significant reduction in flame radiation and delivery of a suppression agent to shielded areas. Of the nine suppression methods tested, a significant reduction in radiant flux was achieved with the TAFES unit, the 95 gpm AFFF hand line and the hand line in conjunction with a PKP portable extinguisher. The sounding tube fire was not fully extinguished, but thermal radiation was minimized and no significant shielded burning persisted.

The Twin Agent Fire Extinguishing System (TAFES) performed satisfactorily, but not as well as the AFFF hand line in conjunction with a PKP portable extinguisher. No qualitative difference in suppression action was observed when substituting a PKP portable extinguisher for the PKP side of the TAFES unit. Limited effectiveness was observed when either PKP or Halon 1211 was used without AFFF, demonstrating the effectiveness and necessity of using AFFF to cool the flame region and surfaces which would otherwise cause reignition.

Conclusions:

1. Typical fuel spray fires can produce heat release rates in excess of 50 MW, and produce hazardous conditions in seconds. The actual heat release rate and time to hazard is dependent on the magnitude and orientation of the fuel leak spray, the ignition duration, the proximity of other equipment and obstructions, and enclosure and ventilation conditions.
2. Discounting enclosure effects, the dominant hazard from such spray fires is flame radiation which can cause significant damage to electronics, equipment, and materials as well as burn injuries to personnel.
3. Suppression of such fires required substantial flame cooling and agent delivery to shielded burn areas.
4. Significant reduction in radiant flux occurred in tests with the TAFES unit, the 95 gpm AFFF hand line, and the hand line in conjunction with a 27 lb PKP portable.
5. No qualitative difference was observed when substituting a PKP portable extinguisher for the PKP side of the TAFES unit.
6. Available deployment time for manual suppression is extremely short, frequently less than 30 seconds for the conditions developed in this test series.
7. A significant reignition hazard existed if the surfaces on which the spray jet impinged were not cooled below the spontaneous ignition temperature of the fuel. AFFF in sufficient quantity was the only agent evaluated in this test series with this capability.

The results of this large scale test series indicate that the available time to deploy manual fire suppression is very short; in some cases it is probably a matter of seconds.

However, due to the potential damageability of electronics and machinery equipment and the lack of performance data for total flooding automatic suppression systems under such conditions, a more detailed examination of manual suppression procedures may be desirable and warranted. Such an examination would include verification testing of optimum suppression methods and tactics, an evaluation of required deployment time, personnel and reentry fire fighter protection, enclosure effects on hazard development time, and the performance of fixed, automatic suppression systems on typical spray fires.

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Appendix A

Summary of U.S. Navy Spray Fire Incidents

SHIP	JAG No.	INCIDENT DESCRIPTION/LOCATION	FUEL TYPE	EXTINGUISHING AGENTS/ METHOD
1. USS CONSTELLATION CVA 64	1256-63	Vibration caused fuel oil flange to open in MAIN MACHINERY SPACE	Fuel Oil (high pressure system, 1000 psi)	AFFF Hose lines
2. USS KITTY HAWK CVA 63	5491-66	Failure of a valve gasket on a fuel filling line in No. 3 MACHINERY SPACE	JP-5	Unknown
3. LCU 1613	3287-71	Rupture of lube oil pressure line from reduction gear sump in ENGINE ROOM	Lube Oil	Portable CO_2
4. USS ASHEVILLE PG 84	4857-72	Rupture of fuel oil return line in ENGINE ROOM	Fuel Oil	None (self extinguished after setting condition ZEBRA)
5. USS CONSTELLATION CVA 64	3655-73	Fuel oil spray during repair in MAIN MACHINERY SPACE	Fuel Oil	AFFF and PKP with Twin Agent Unit (TAU)
6. USS AGERHOLM DD 826	5205-73	Rupture of boiler burner lead line in FORWARD FIREROOM	Fuel Oil	Water used to cool after securing fuel
7. USS ROARK DE 1053	093-74	Failure of lube oil strainers in ENGINE ROOM	Lube Oil	AFFF Handline & PKP portables
8. USS ENHANCE MSO 437	499-74	Hole in fuel oil line caused fuel spray fire in FORWARD ENGINE ROOM	Fuel Oil	AFFF Sprinklers and hose lines

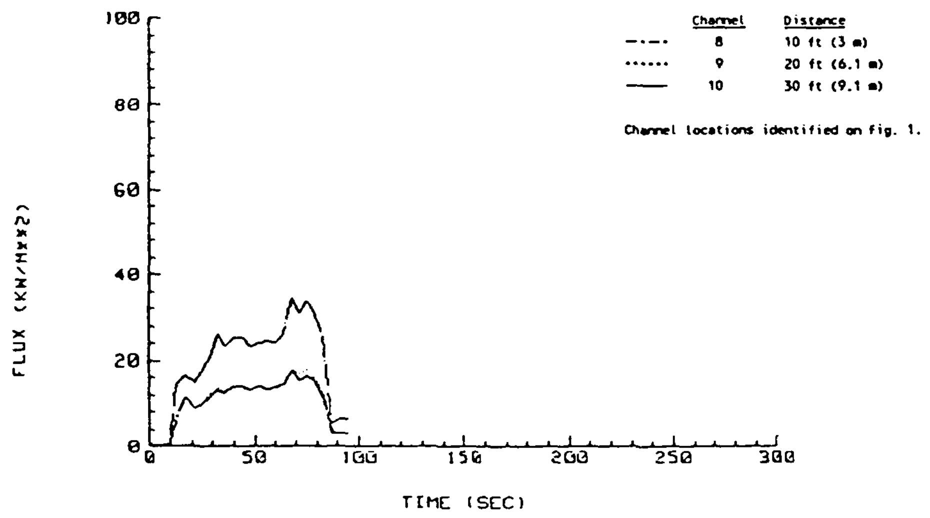
SHIP	JAG No.	INCIDENT DESCRIPTION/LOCATION	FUEL TYPE	EXTINGUISHING AGENTS/ METHOD
9. USS RANGER CV 61	2280-74	Fuel oil spray from sounding tube in MAIN MACHINERY ROOM	Fuel Oil	AFFF hose line
10. USS SILAS BENT TAGS 26	4136-74	Fuel leak in AUX. GENERATOR ROOM	Fuel Oil	Carbon dioxide hosereel water hose line
11. USS SHANGRILA CVS 38	5045-75	During aircraft refueling fuel nozzle disengaged on FLIGHT DECK	JP-5	Water hose line PKP & CO_2 portable
12. USS RAMSEY DEG 2	850-77	Failure of JP-5 fuel line connection on a boiler in FIRE ROOM	JP-5	PKP & AFFF with TAU
13. USS KITTY HAWK CV 63	3249-75	Failure of fuel fill line strainer in MAIN MACHINERY SPACE	Fuel Oil	AFFF hose line
14. USS EDSON DD 946	4593-77	Broken lube oil gage line resulted in spray fire in FIRE ROOM	Lube Oil	Water hose line
15. USS ALBANY CG 10	3243-76	Failure of fuel oil strainer in #2 FIRE ROOM	Fuel Oil	Water and AFFF hose line
16. USS INFLICT MSO 46	329-77	Ruptured lube oil line in ENGINE ROOM	Lube Oil	PKP portable
17. USS PRESERVER ARS 8	2818-77	Fuel spray fire in MACHINERY ROOM	JP-5	Water hose line AFFF hose line

SHIP	JAG No.	INCIDENT DESCRIPTION/LOCATION	FUEL TYPE	EXTINGUISHING AGENTS/ METHOD
18. USS HULL DD 945	5539-77	Rupture of lube oil gage line in FIRE ROOM	Lube Oil	PKP and AFFF with TAU
19. USS COCOPA ATF 101	2669-78	Pressure load-up caused fuel oil spray fire in MOTOR ROOM	Fuel Oil	Water hose line
20. USS FAIRFAX COUNTY LST 1193	544-79	Leak in lube oil sensing line caused spray fire in ENGINE ROOM	Lube Oil	Water hose line PKP and AFFF with TAU
21. USS STANDLEY CG 32	5514-86	Open sounding tube near the boiler caused spray fire in ENGINE ROOM	Fuel Oil	Halon 1301
22. USS SCHNECTADY LST 1185	5504-86	Open petcock caused spray fire in No. 1 ENGINE ROOM	Fuel Oil	AFFF hose lines Water hose lines
23. USS NITRO AE 23	1476-82	Open sounding tube caused spray fire in MAIN MACHINERY ROOM	Fuel Oil	Water hose lines PKP and AFFF with TAU
24. USS OLDENDORF DD 972	3228-83	Oil seal rupture on Fuel Oil Purifier in AUXILIARY MACHINE ROOM	Fuel Oil	AFFF Sprinklers Salt water hose lines
25. USS DAVIDSON FF 1045	2003-84	Leak in fuel oil transfer piping in FIREROOM during at sea refueling	Fuel Oil	Water and AFFF hose lines
26. USS HANLEY DD 940	993-80	Fuel spray/leak from burner assembly on 1A boiler in the FIREROOM (1 death)	Fuel Oil	Water and AFFF hose lines

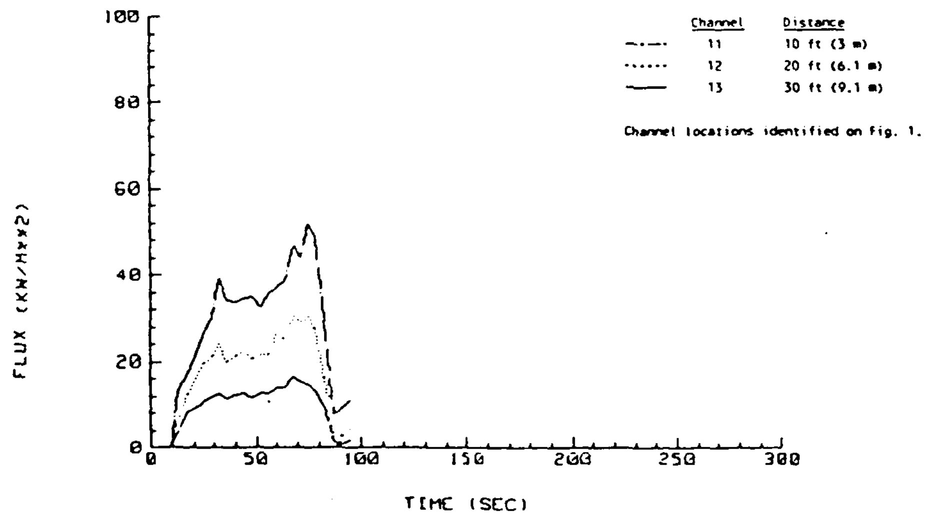
SHIP	JAG No.	INCIDENT DESCRIPTION/LOCATION	FUEL TYPE	EXTINGUISHING AGENTS/ METHOD
27. USS RANGER CV 61	1828-84	Fuel spray from open sounding tube in No. 4 MAIN MACHINERY ROOM (6 deaths)	Fuel Oil	Water and AFFF hose lines, TAU-PKP and AFFF

Appendix B

Phase I Experimental Data



SF001 RADIOMETER PLOTS



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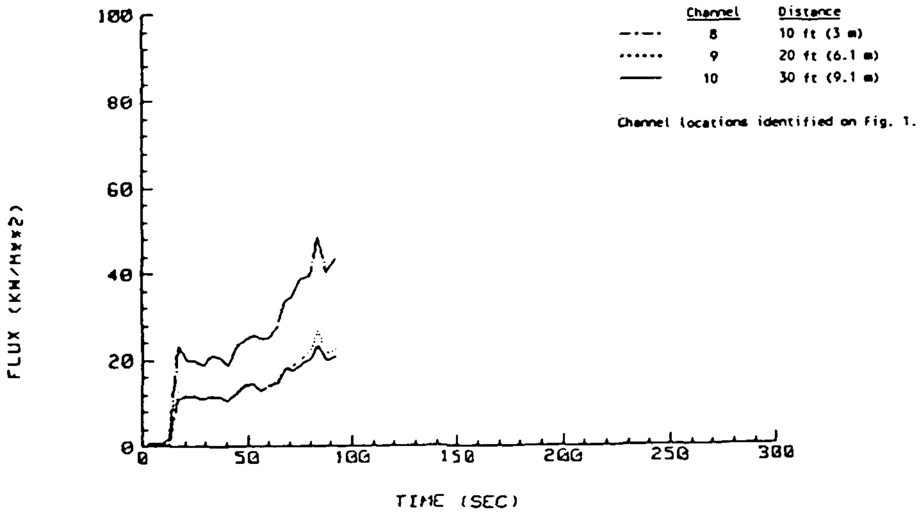

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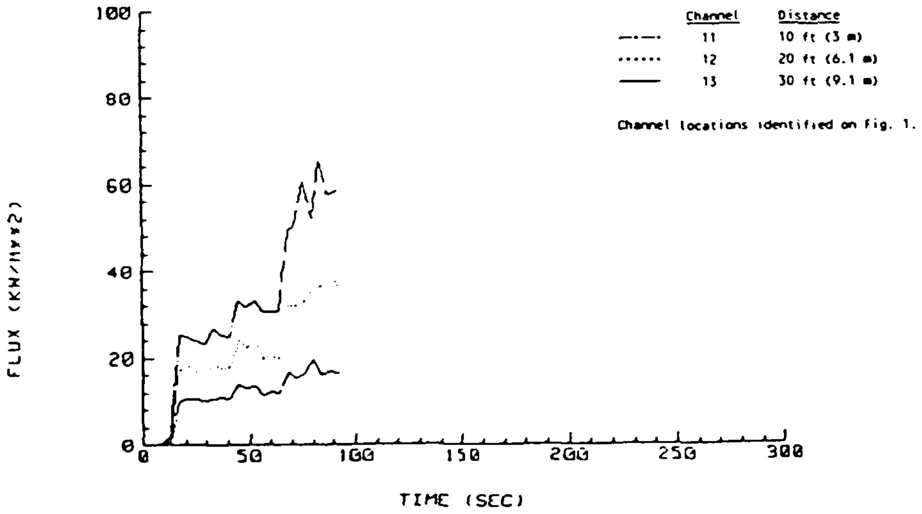

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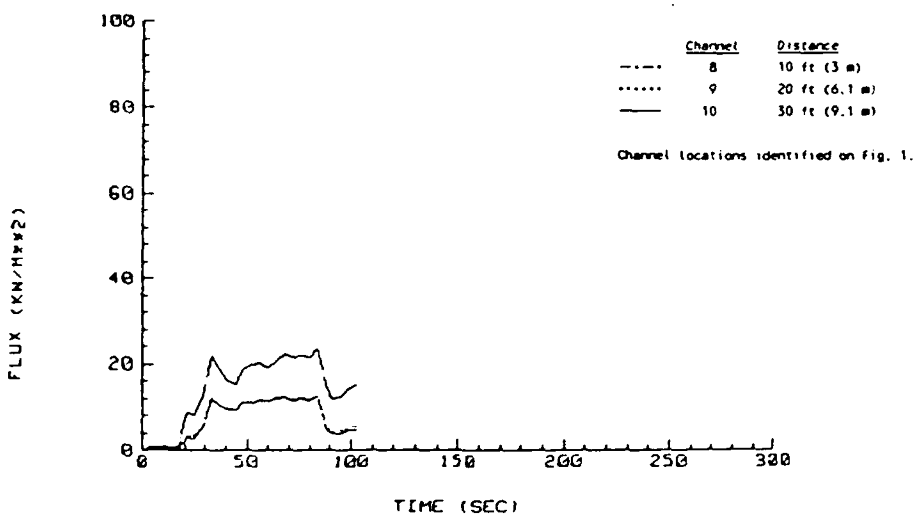

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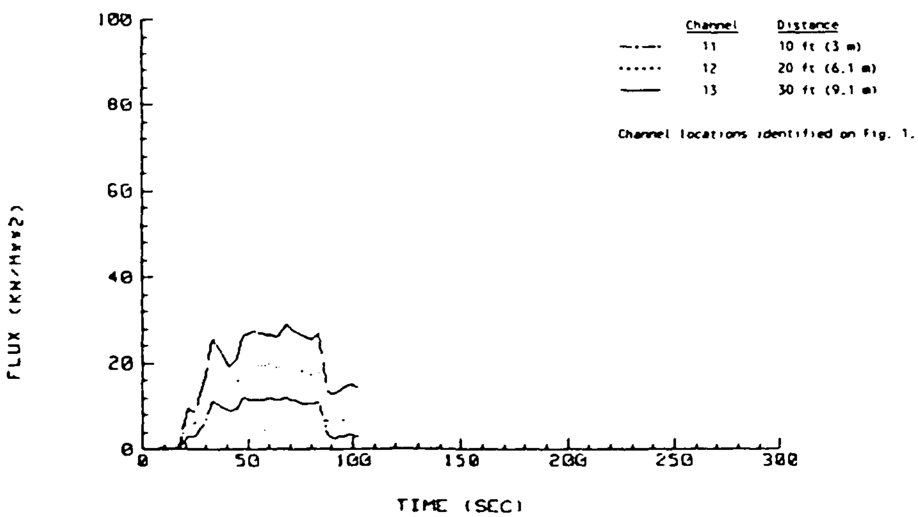

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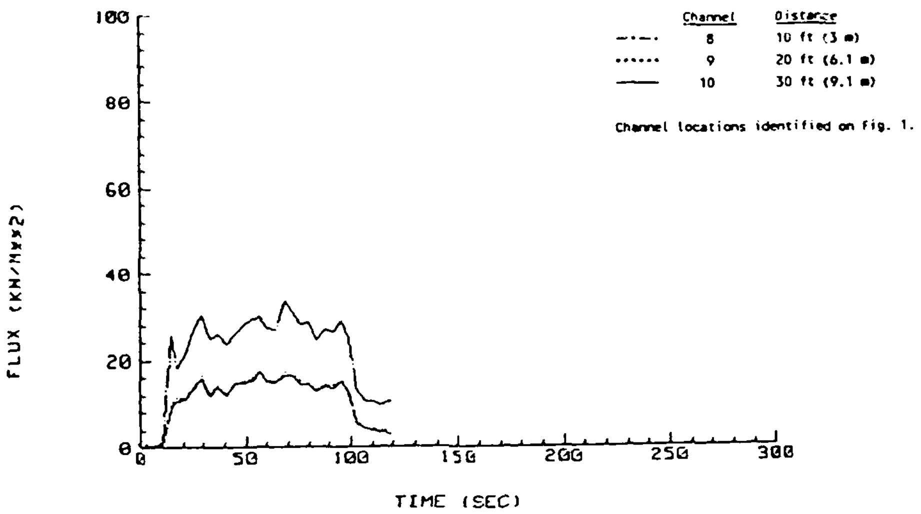
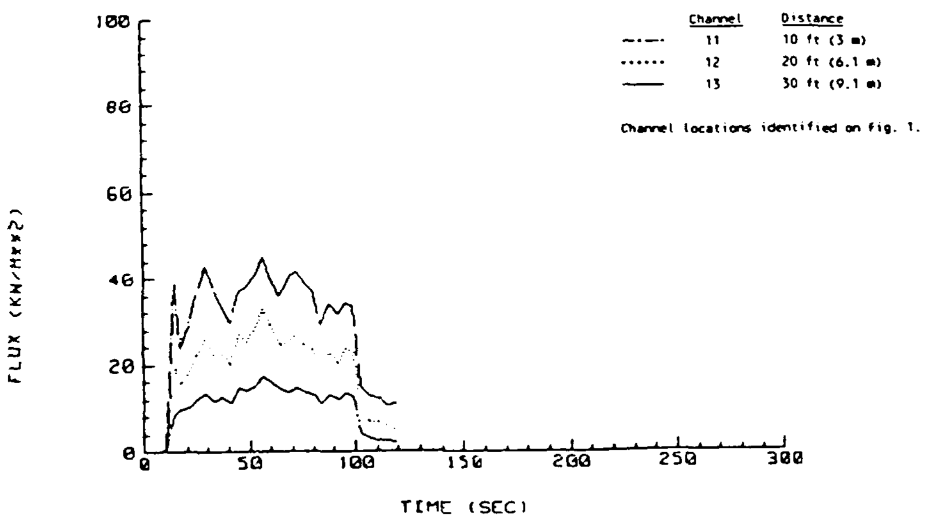


SF004 RADIOMETER PLOTS



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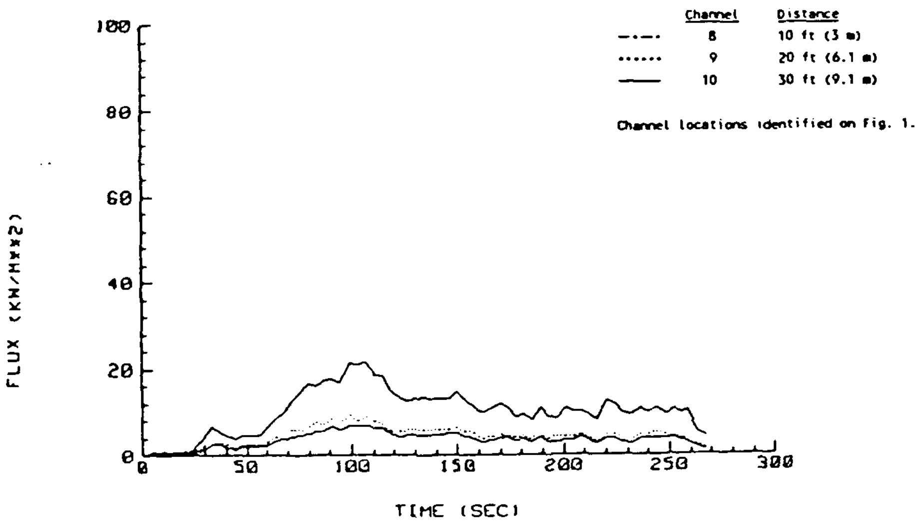
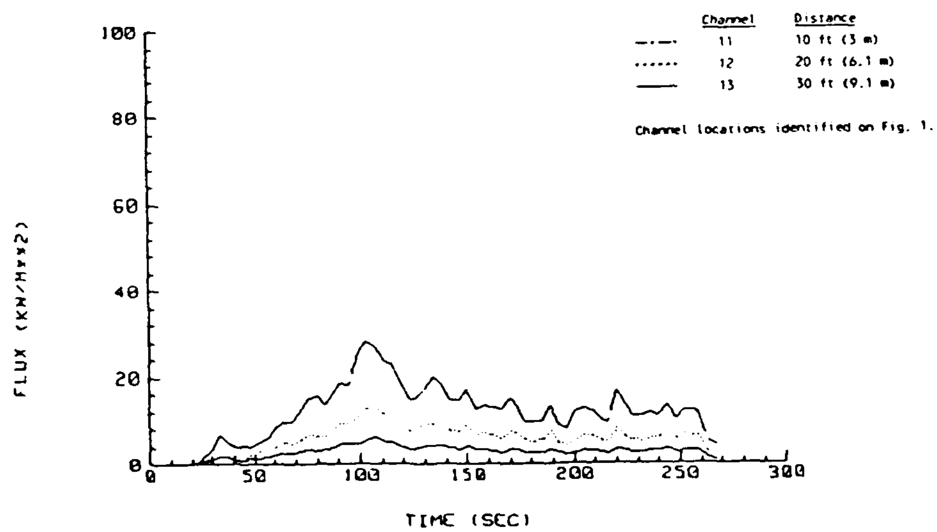


SFØØ5 RADIOMETER PLOTS



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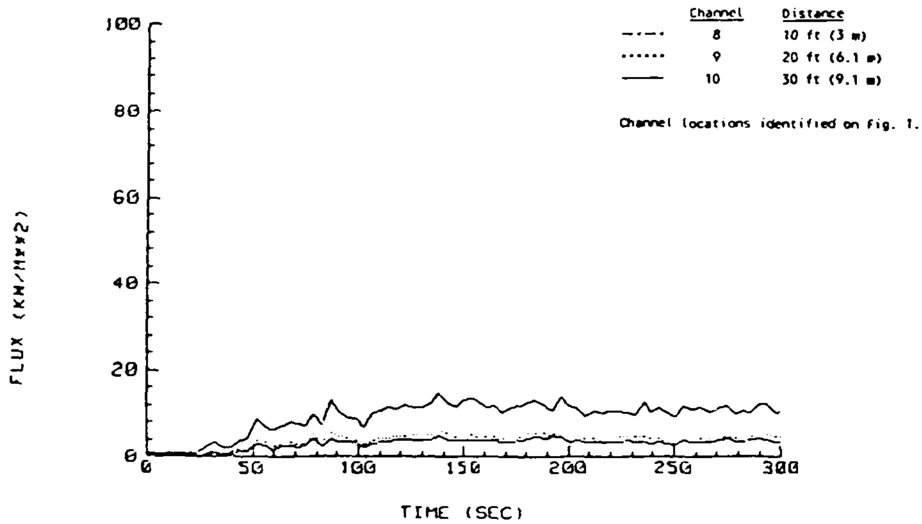

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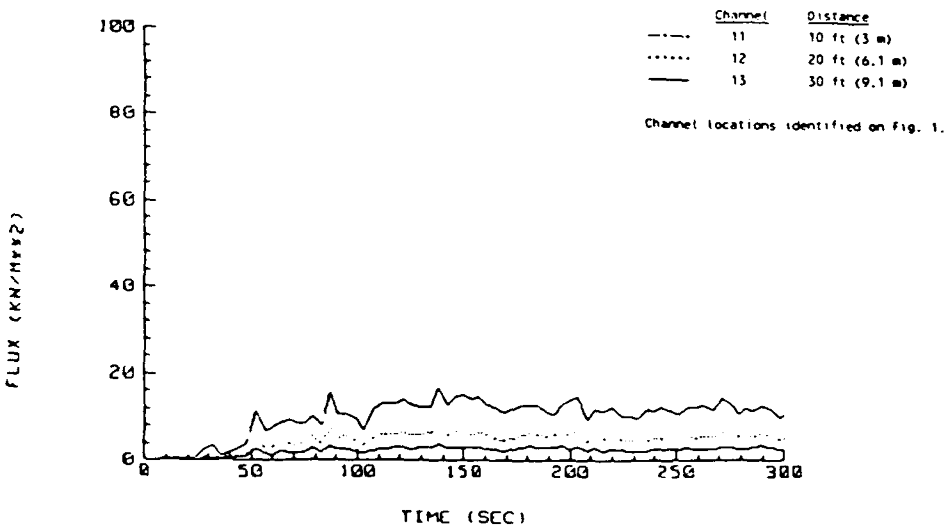

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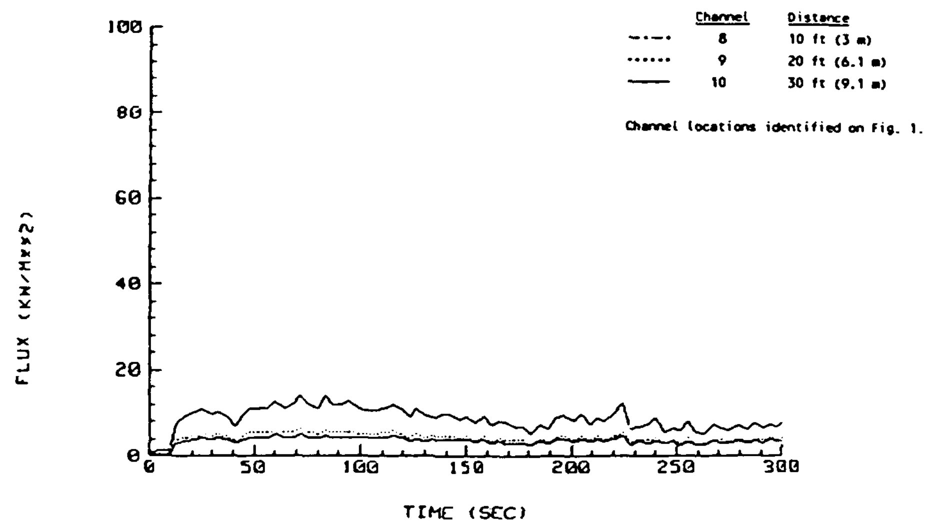

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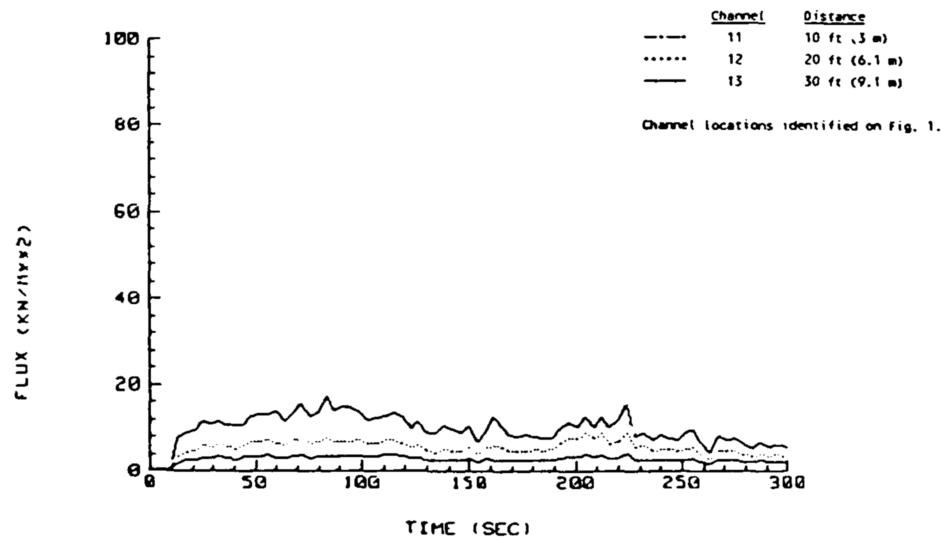

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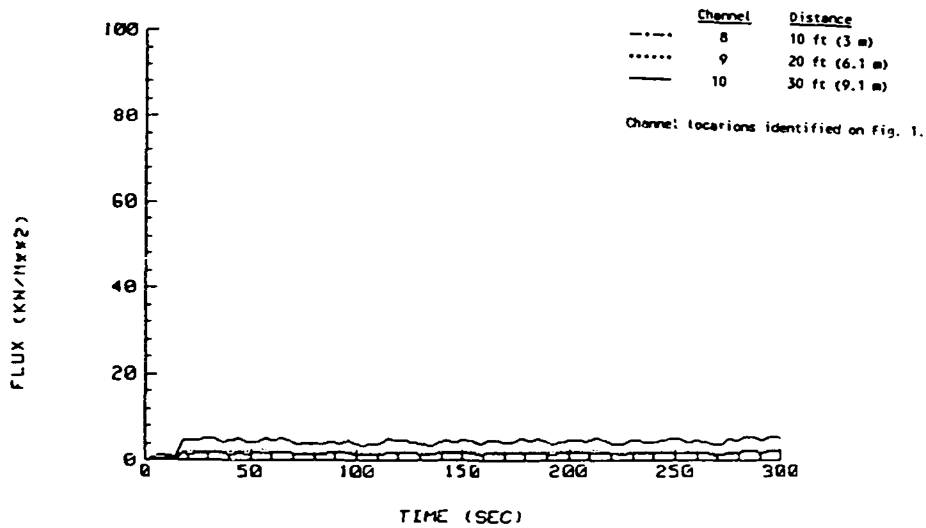

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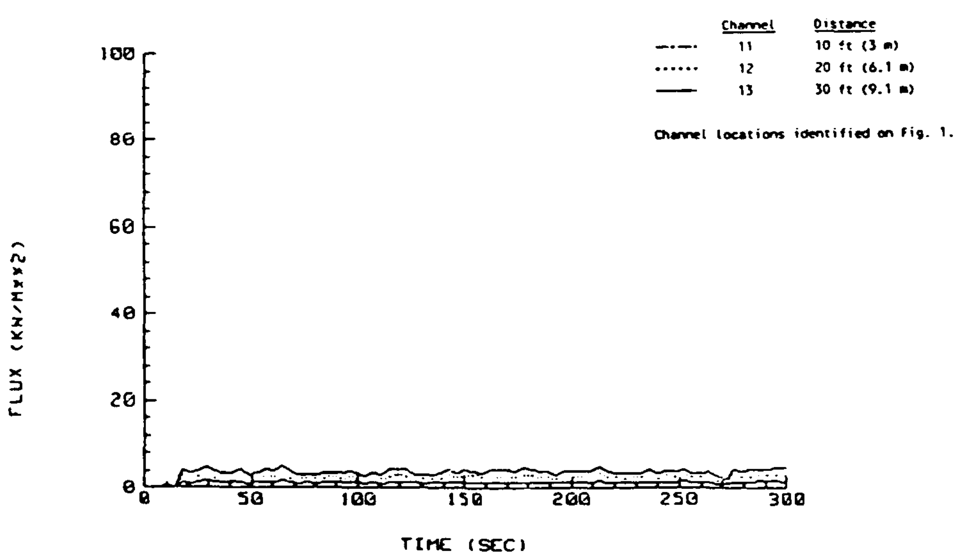

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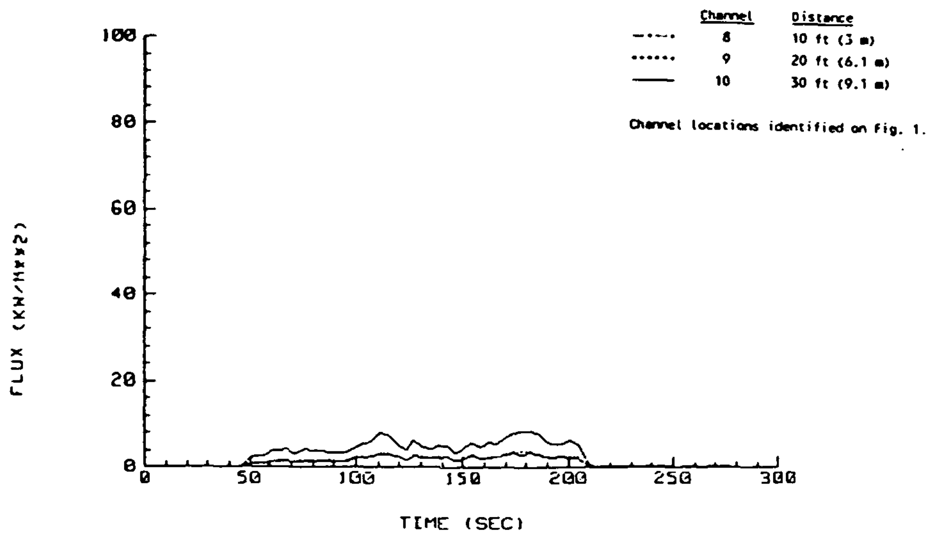

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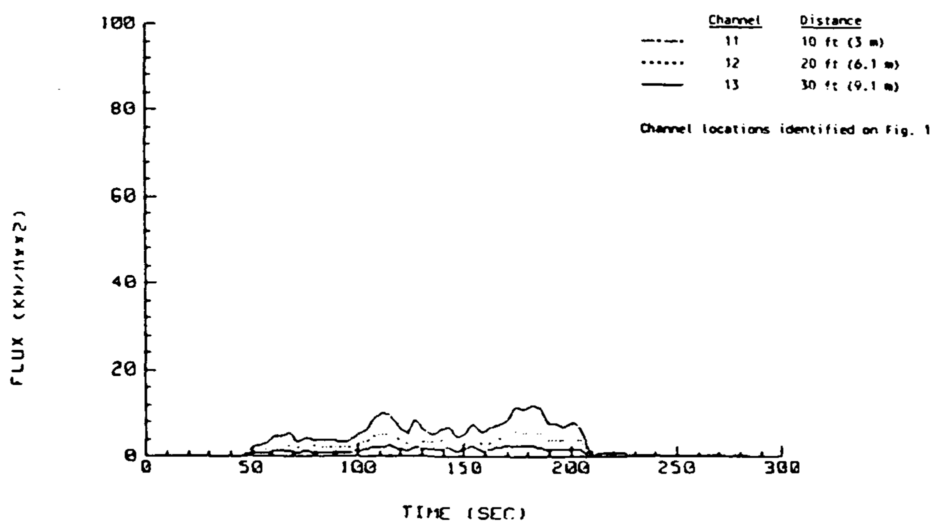

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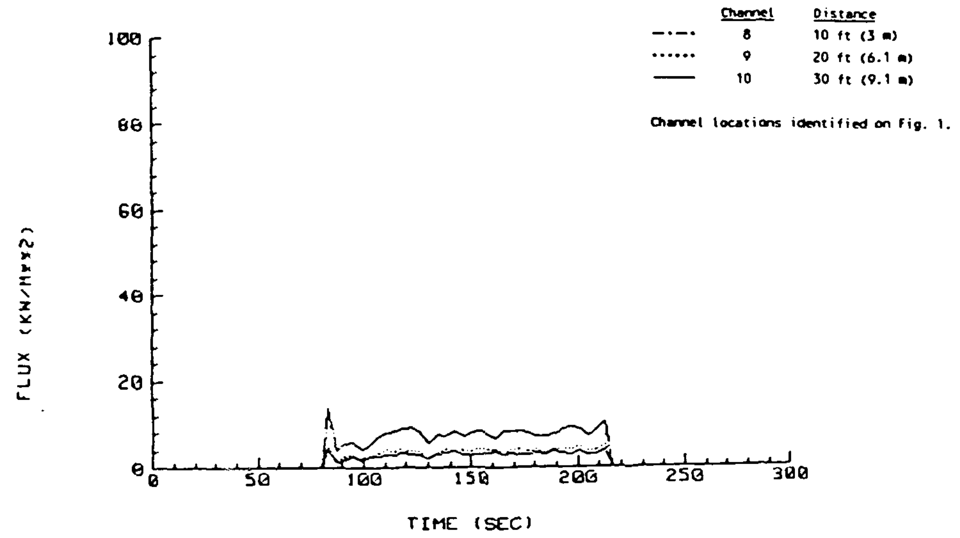

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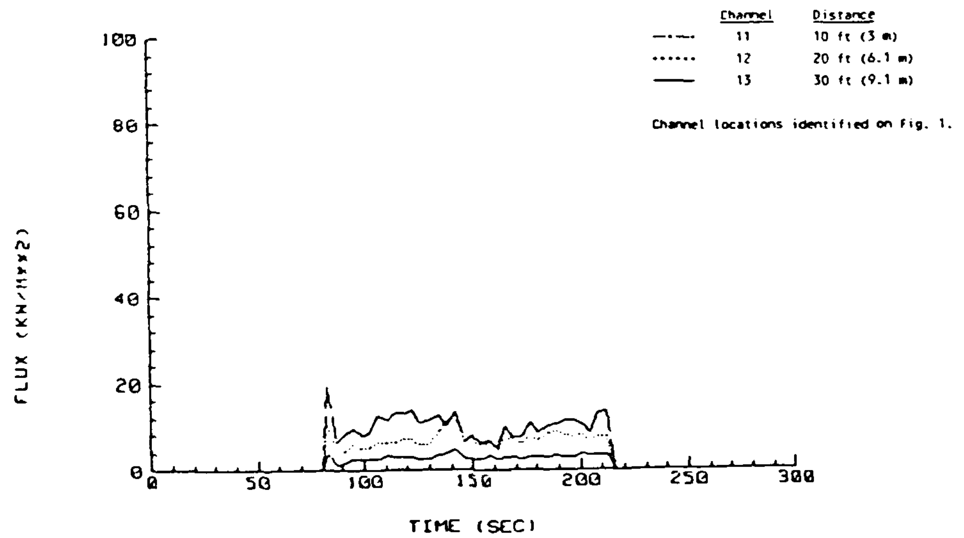

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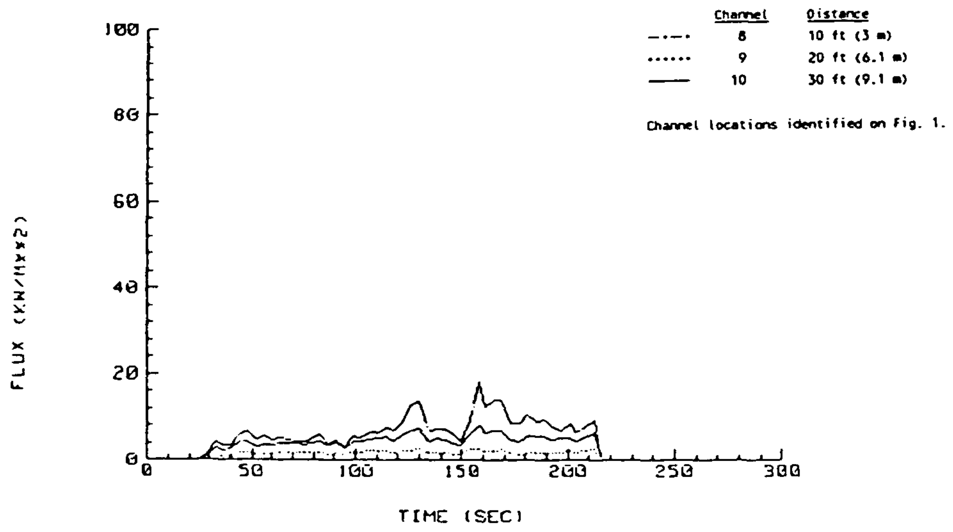

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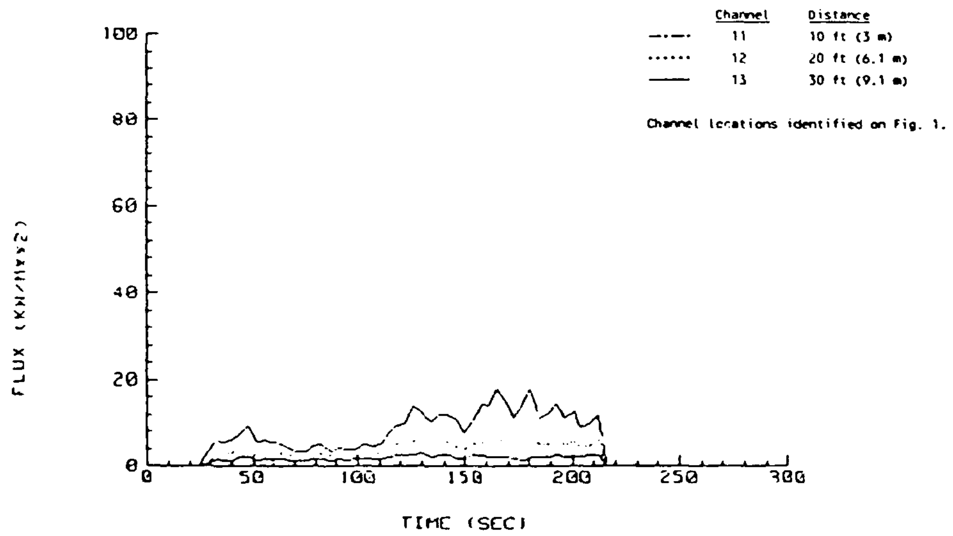

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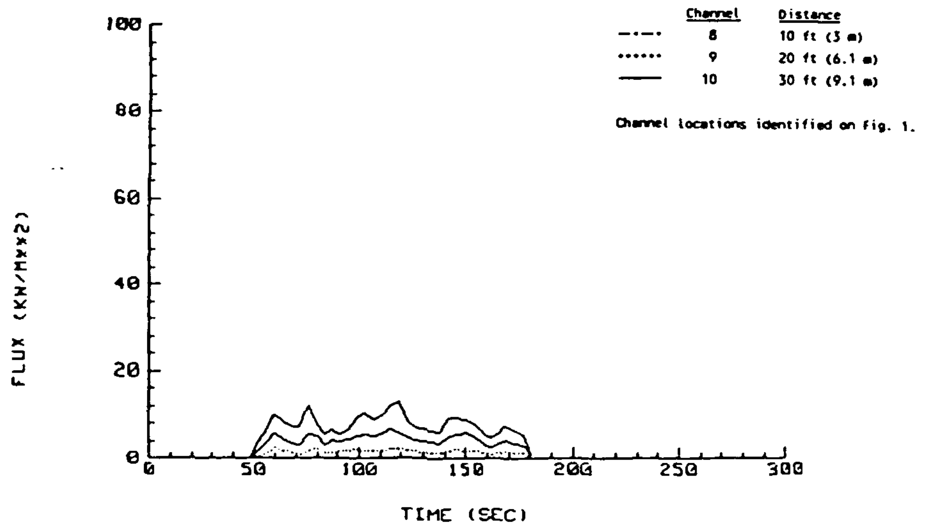

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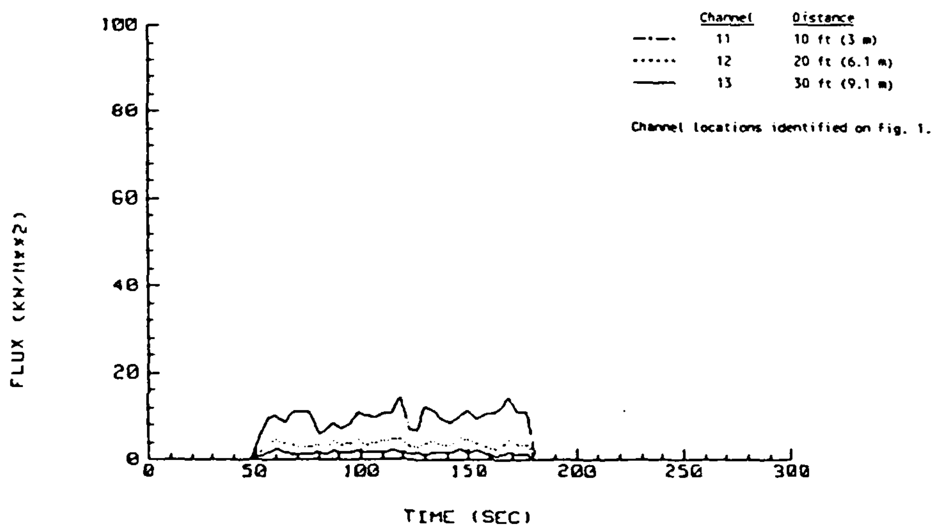

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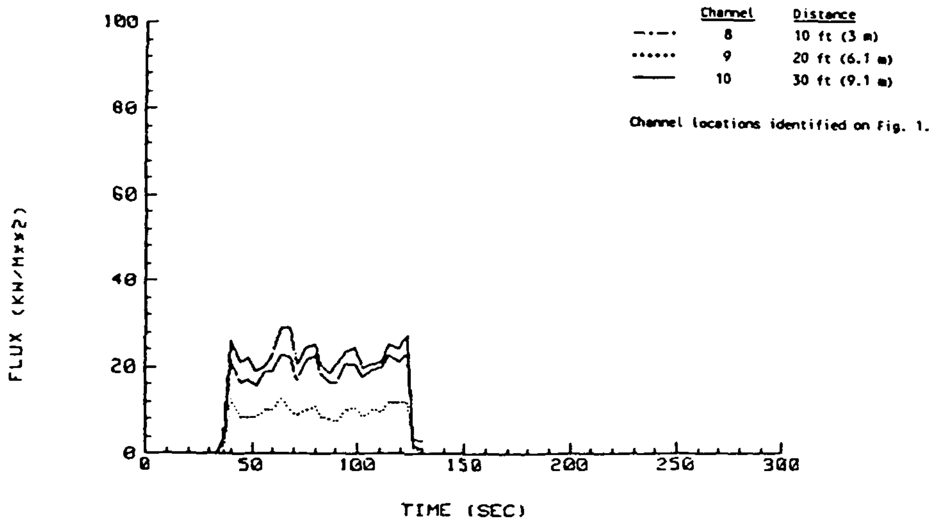

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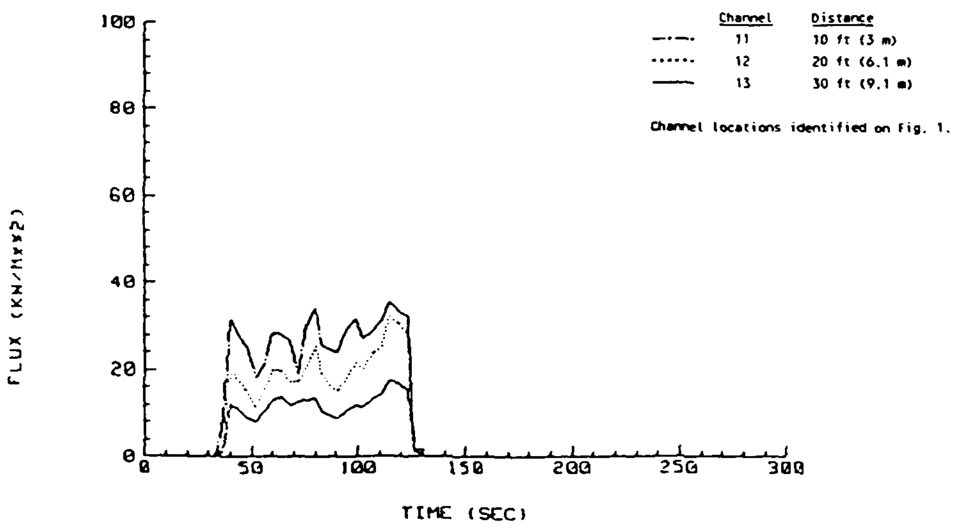

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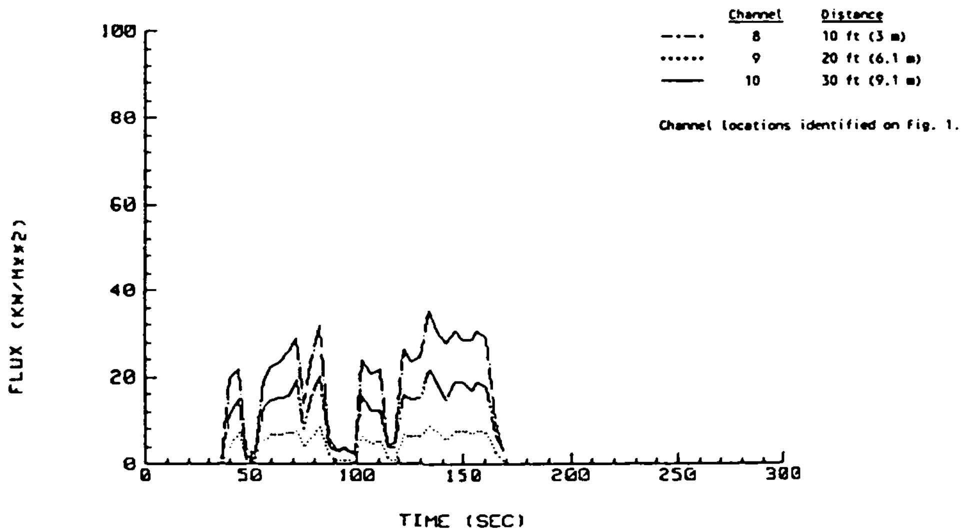

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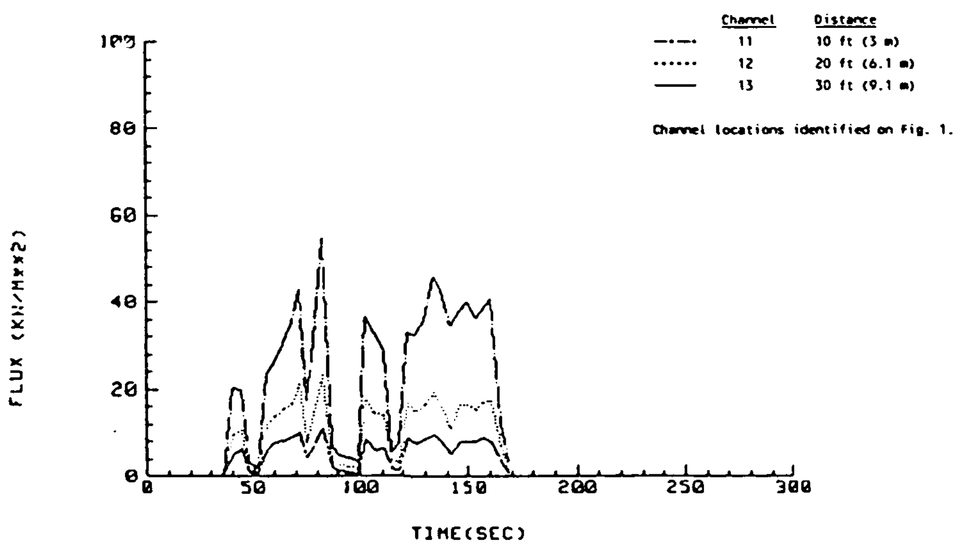
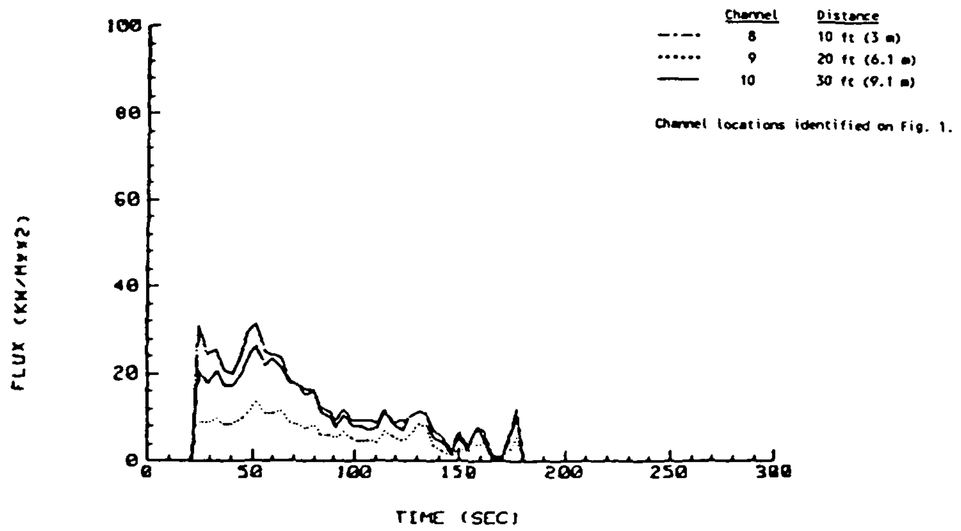


SF014 RADIOMETER PLOTS

Appendix C

Phase II Experimental Data



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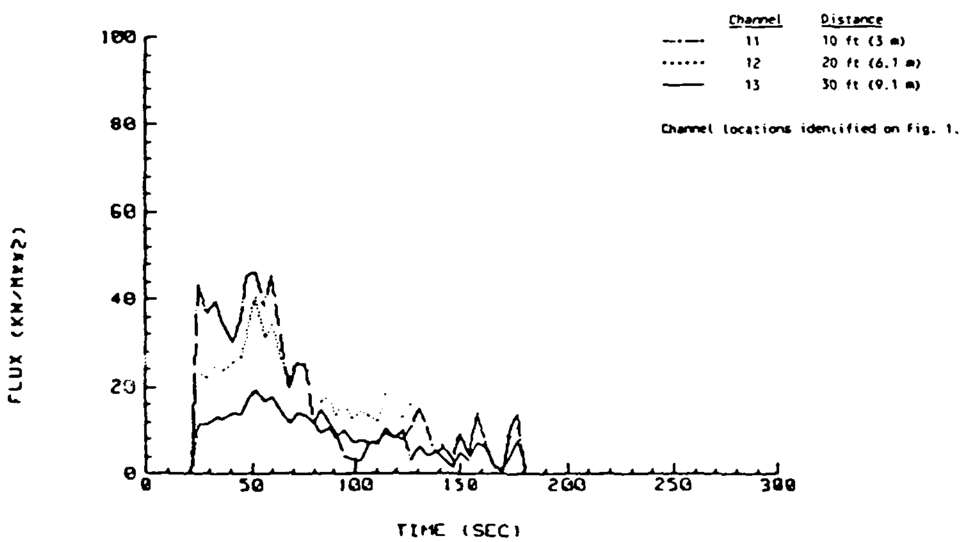

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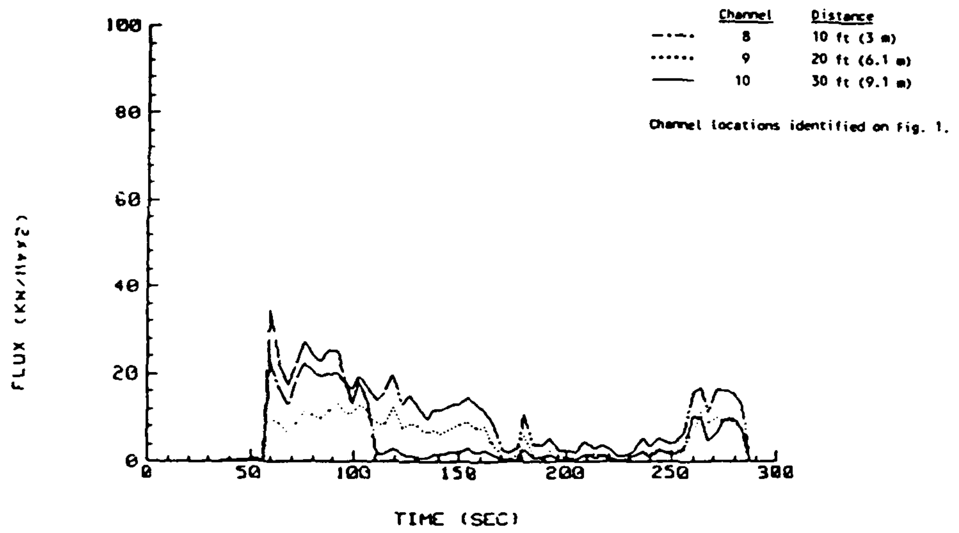

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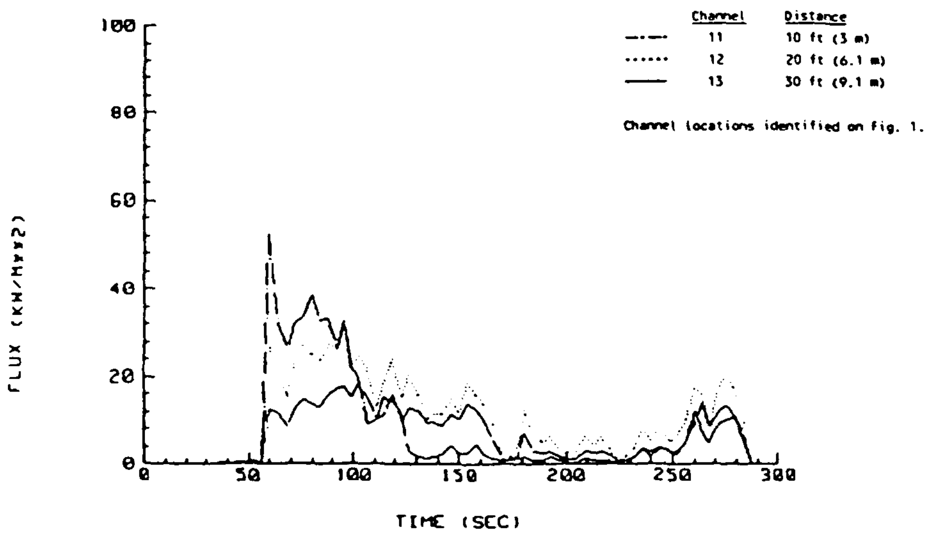

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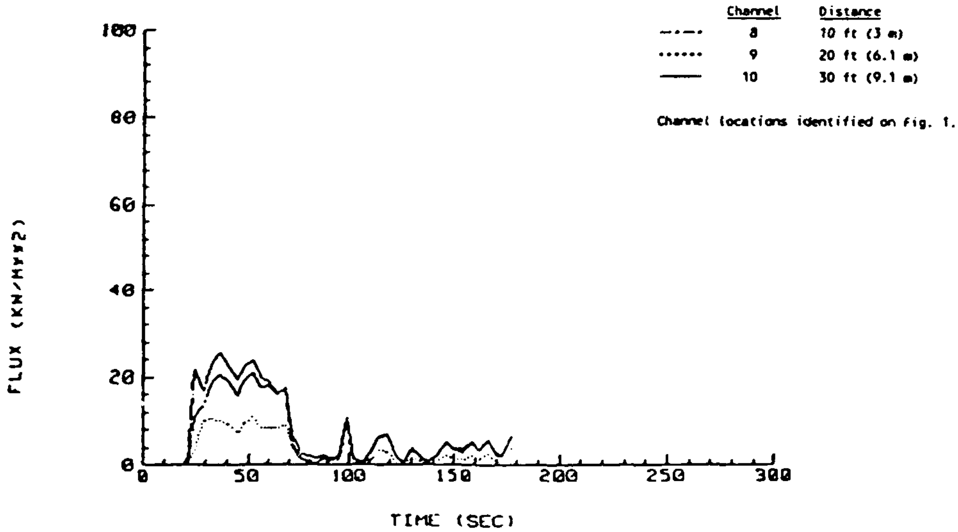

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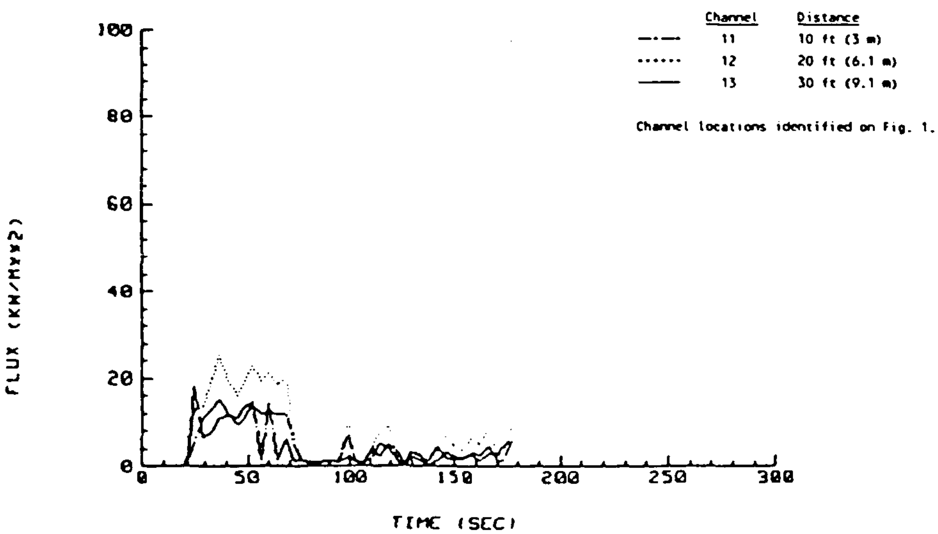

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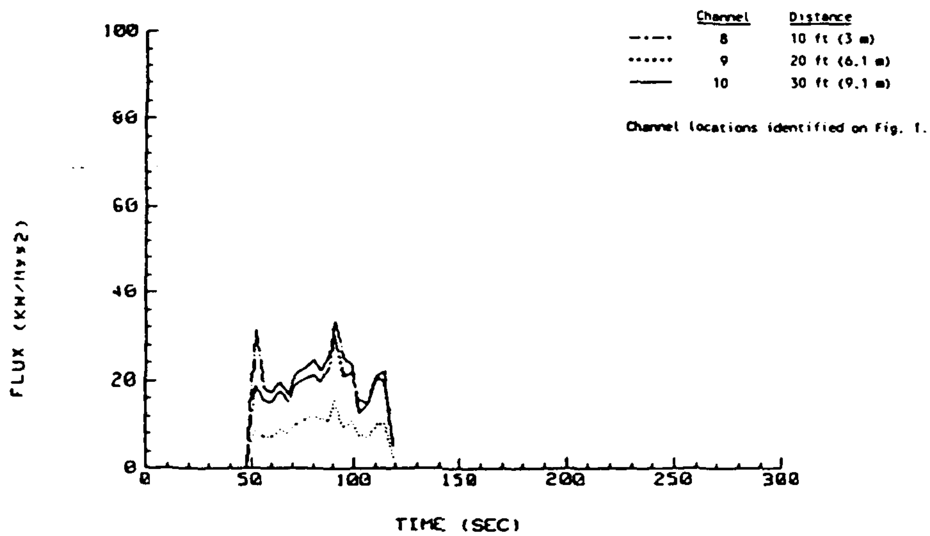

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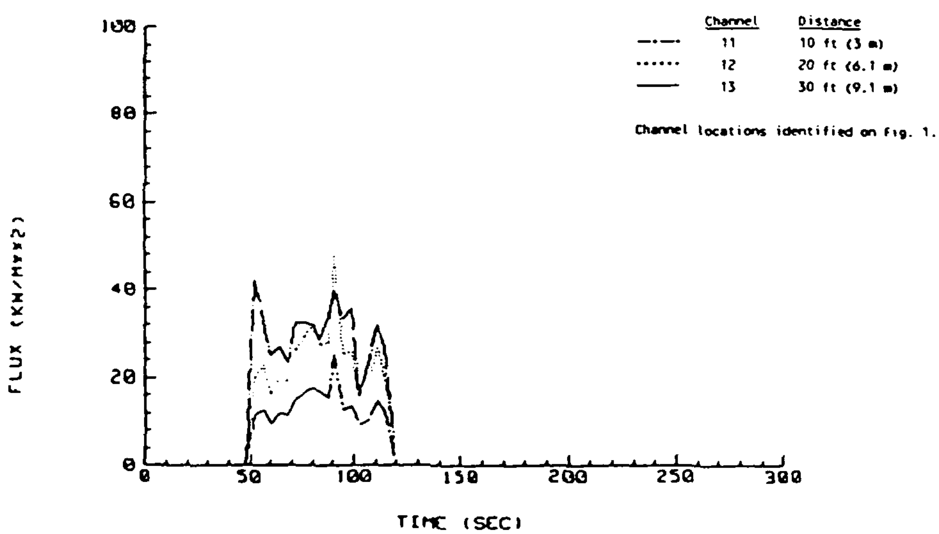

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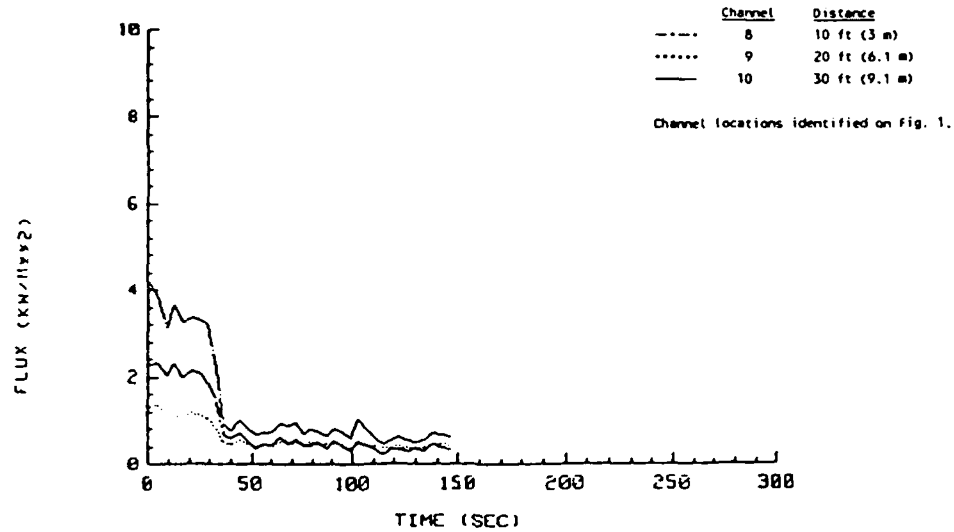

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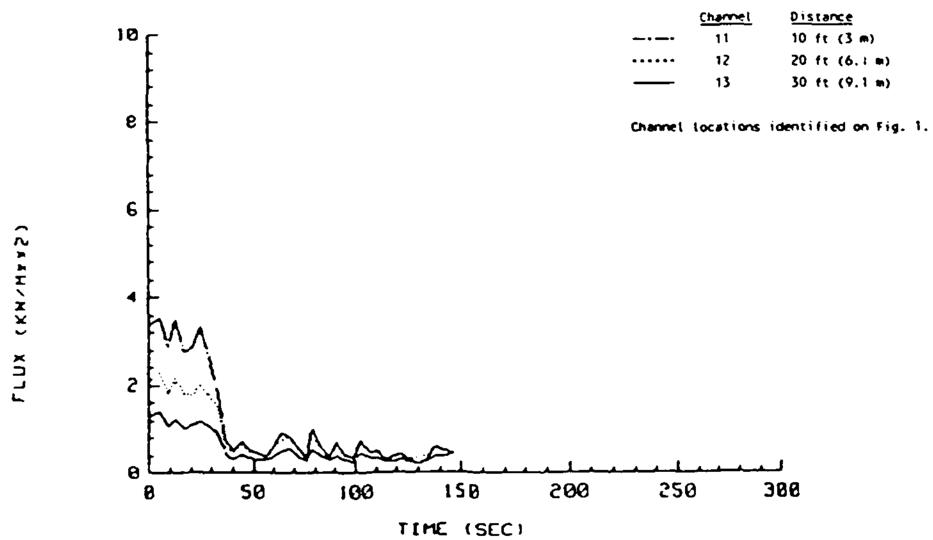

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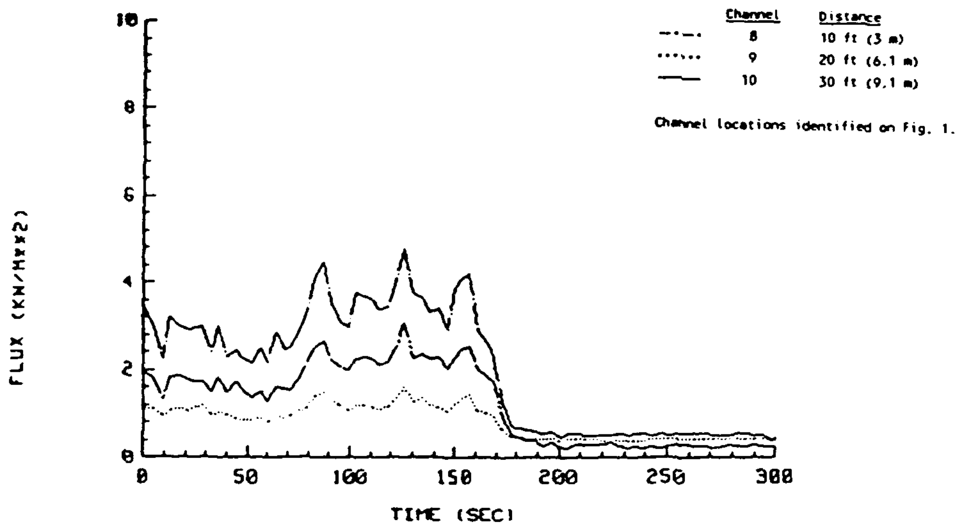

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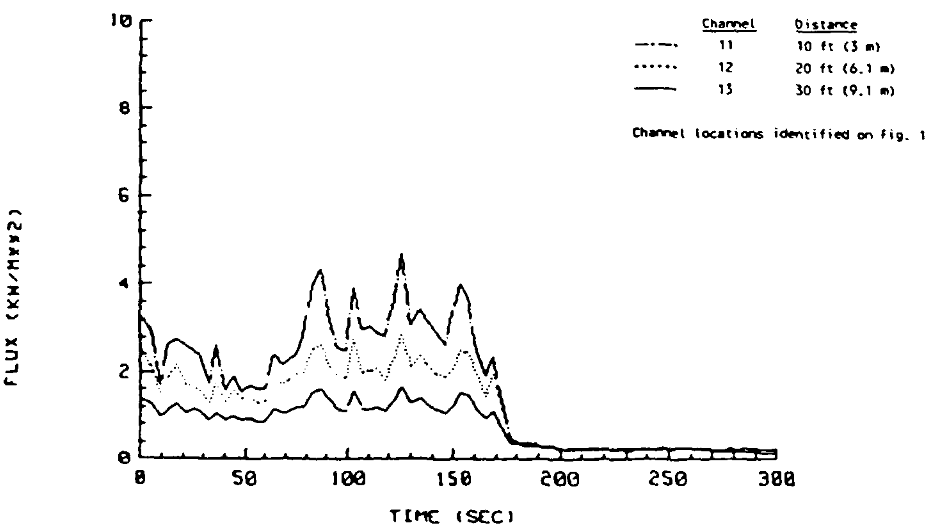

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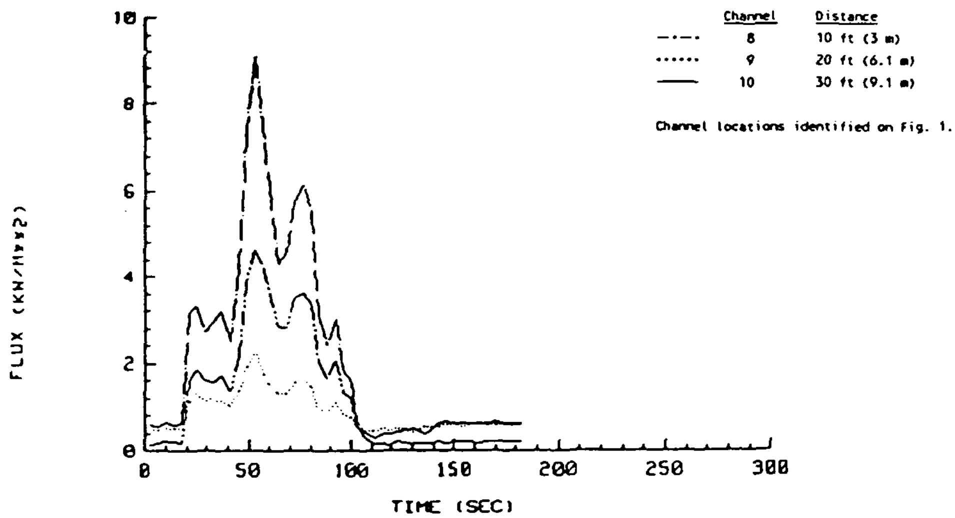

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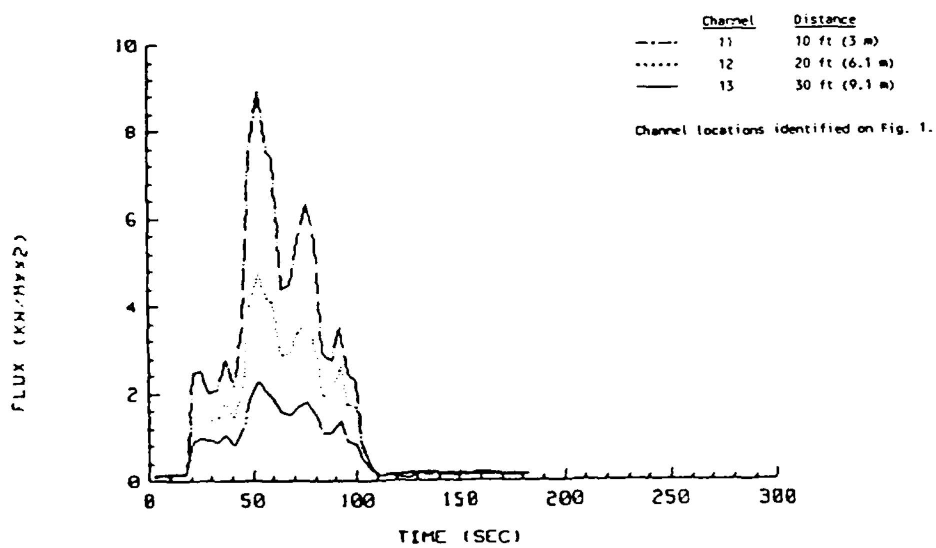

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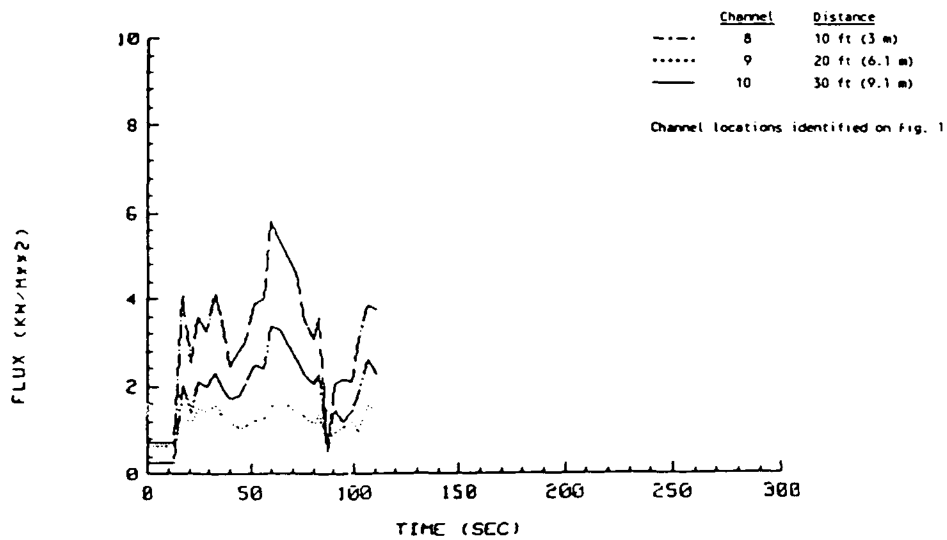

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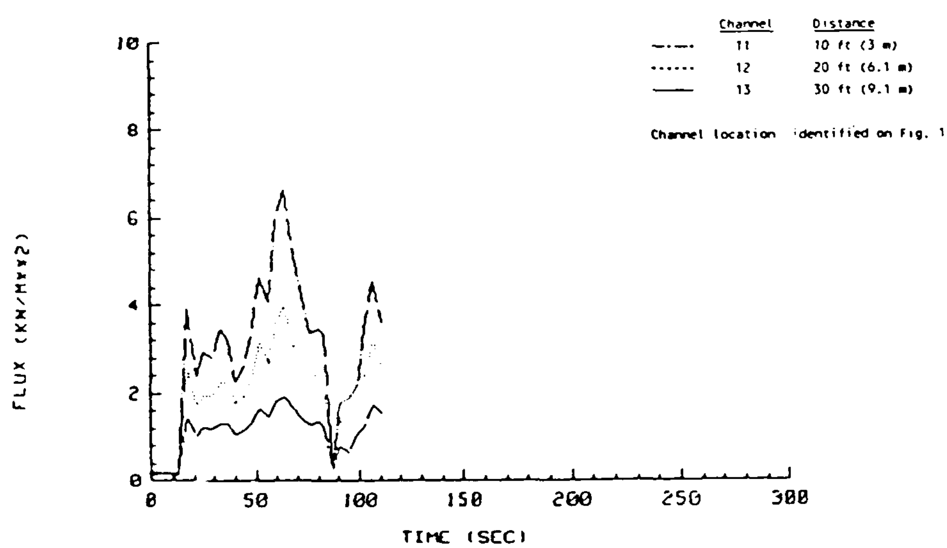

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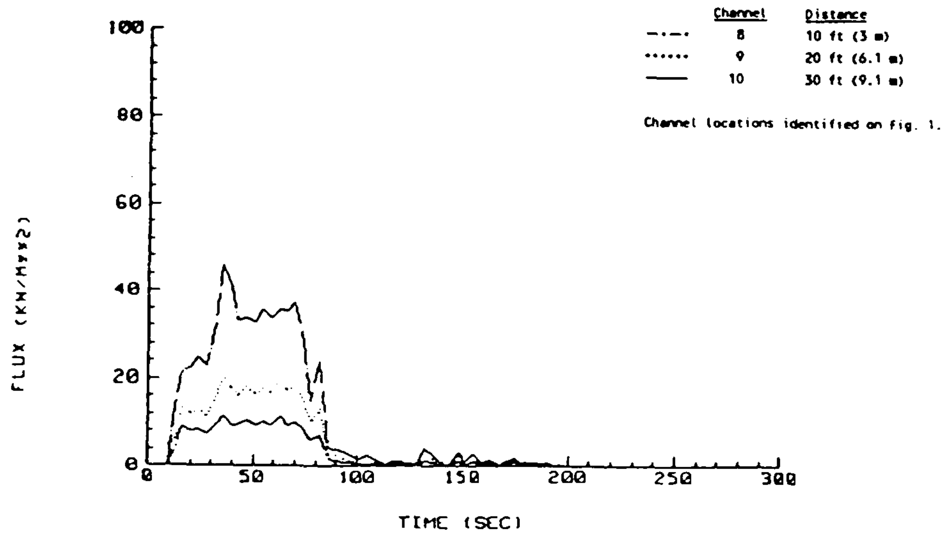

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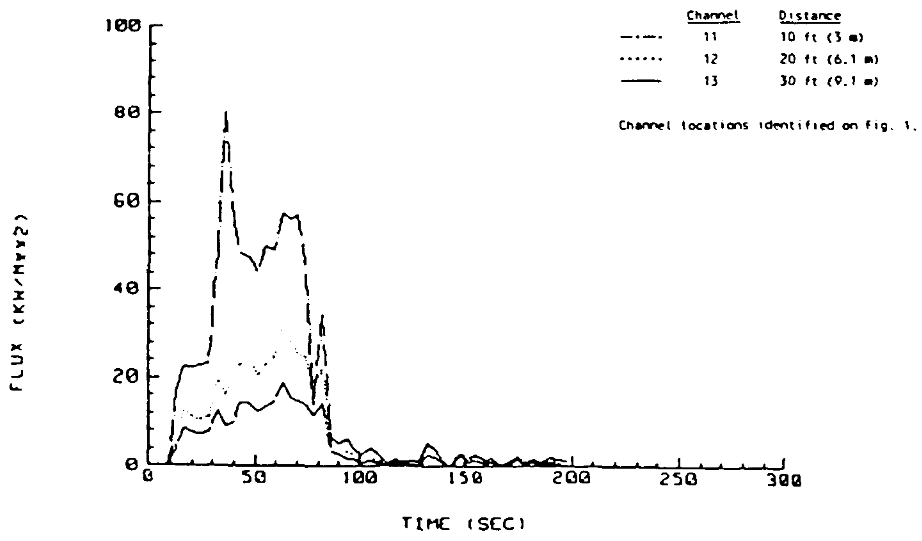

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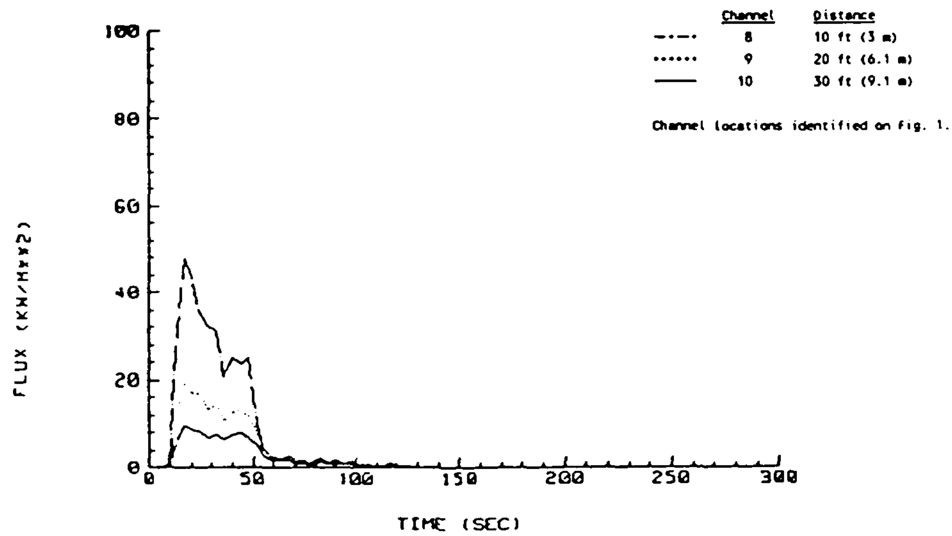

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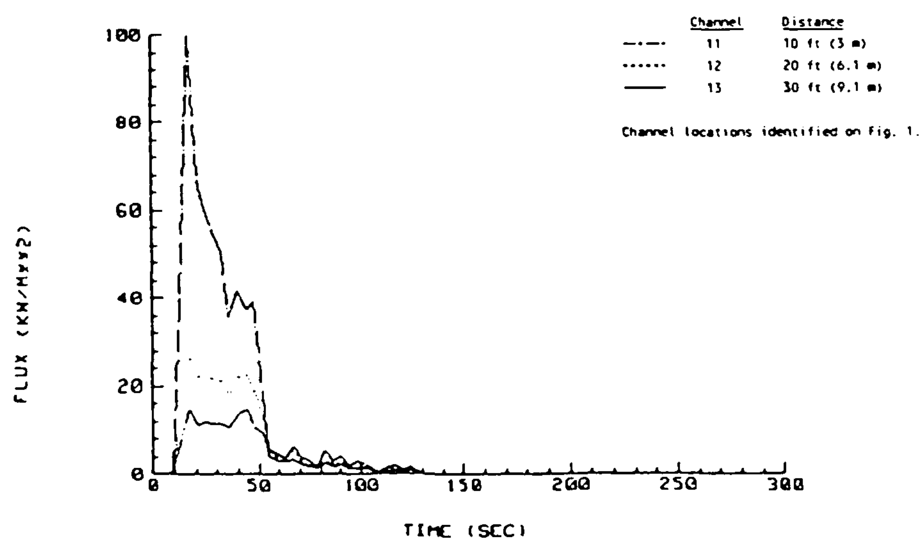

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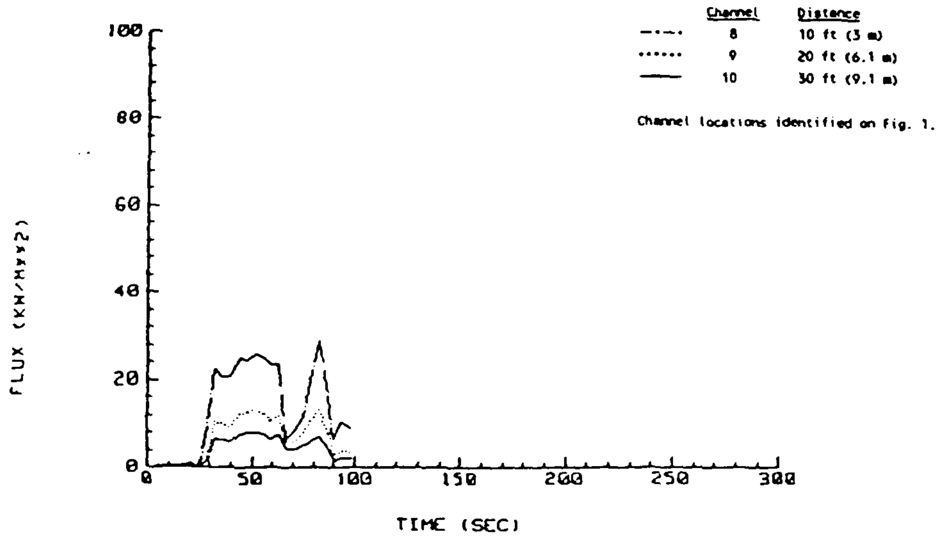

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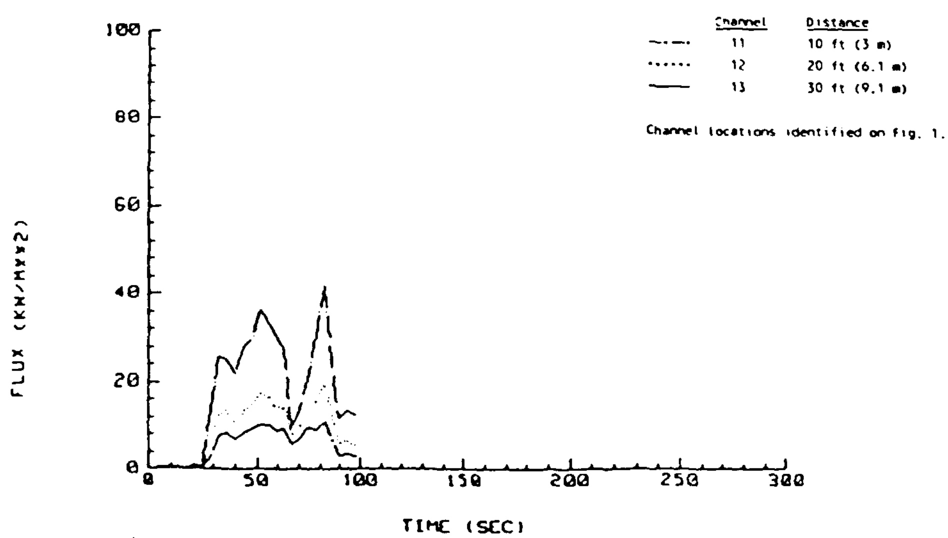

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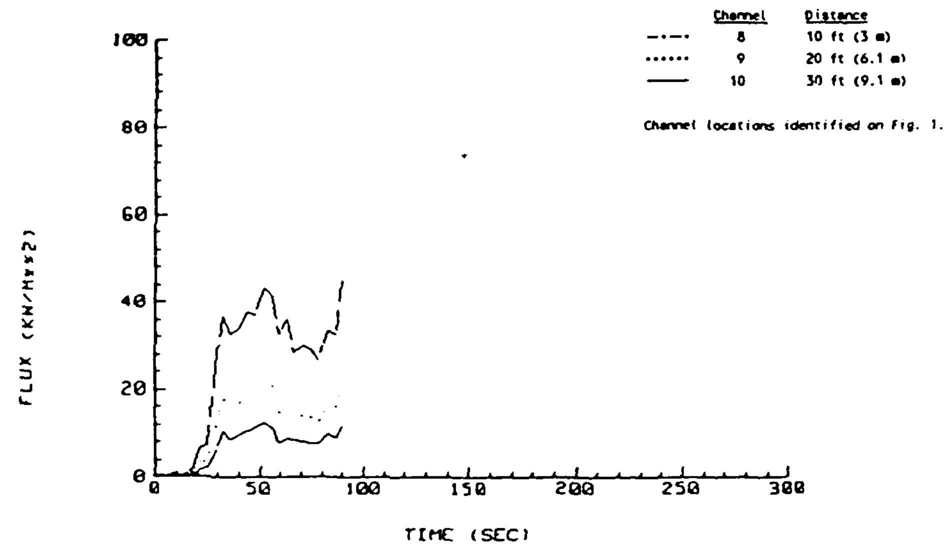

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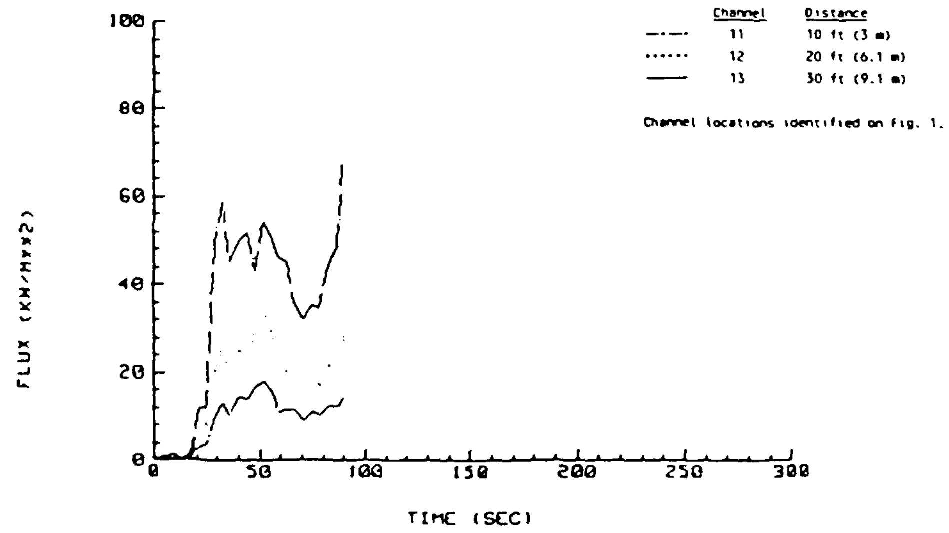

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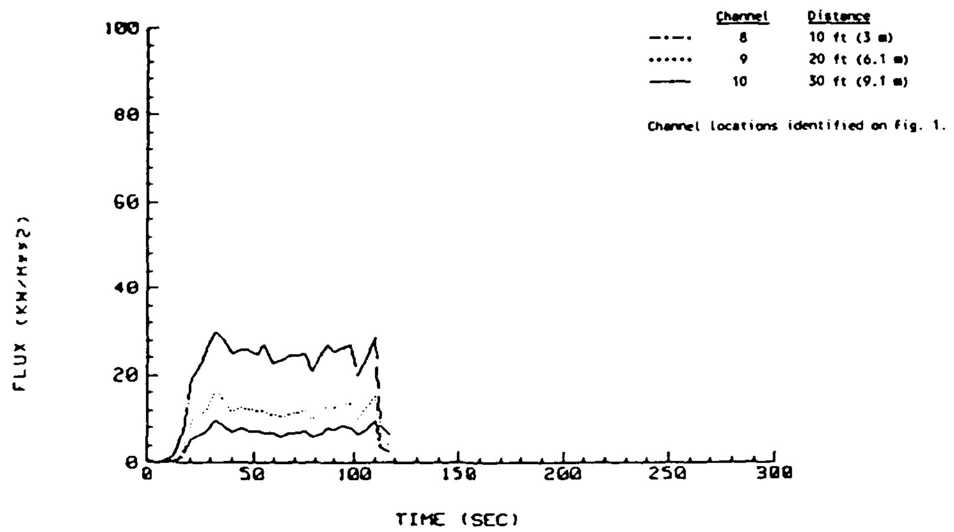

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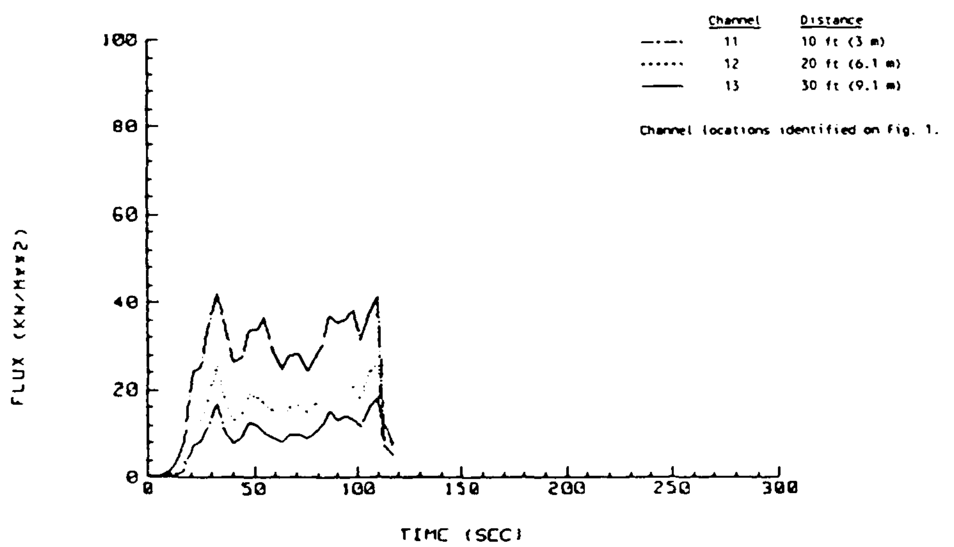

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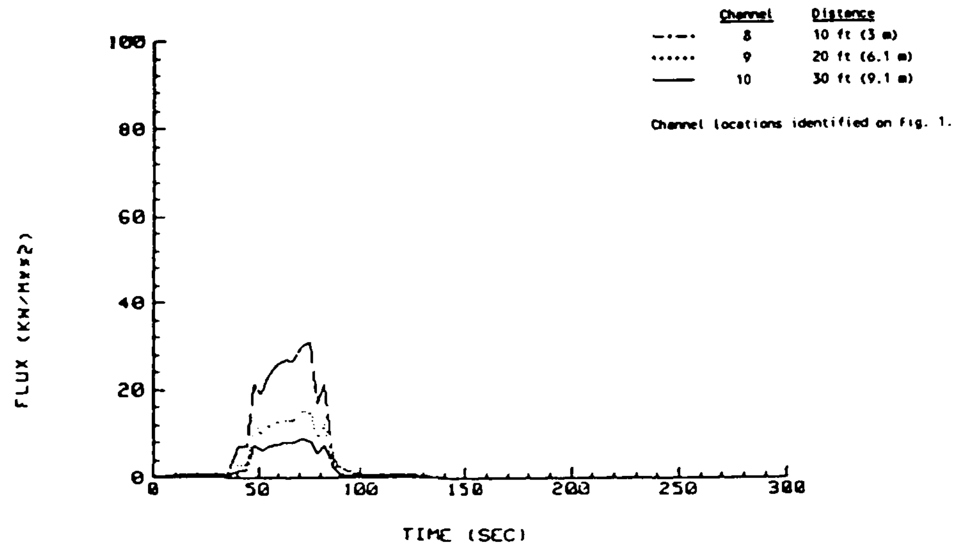

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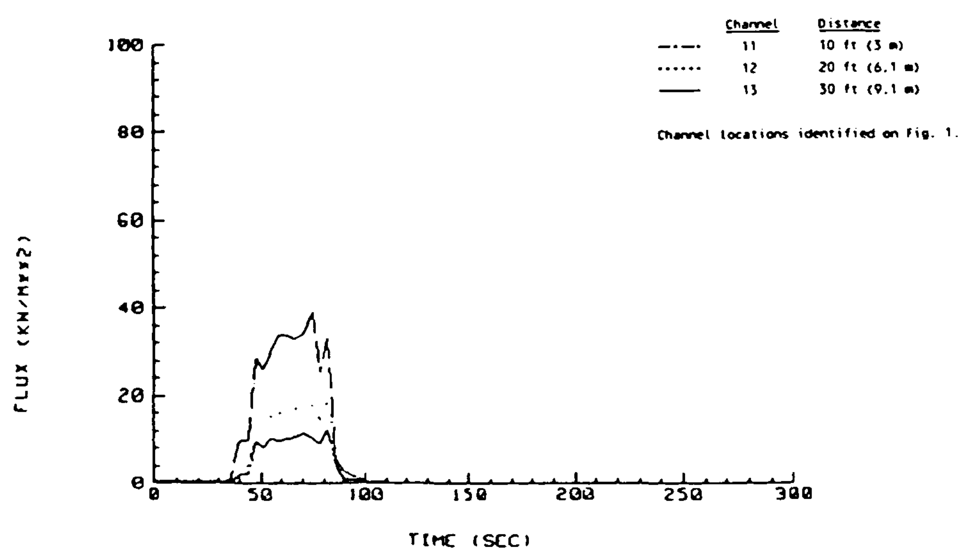

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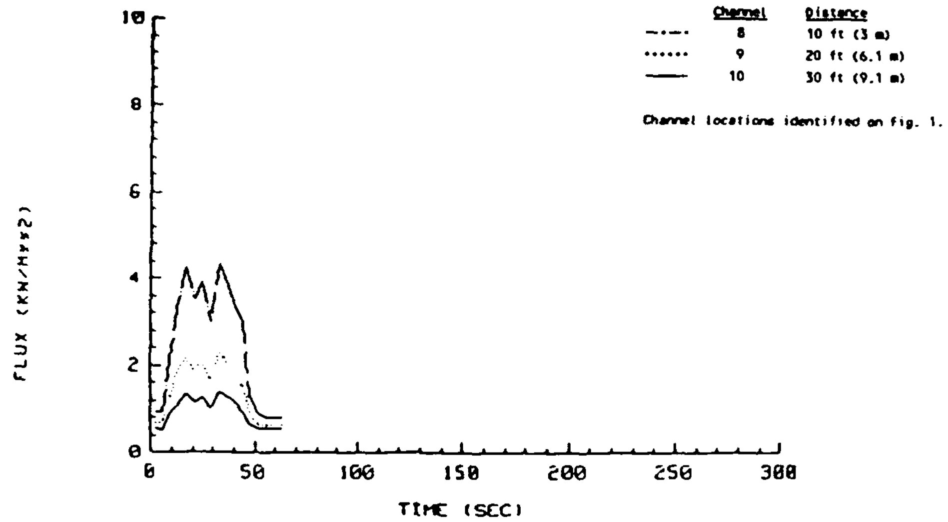

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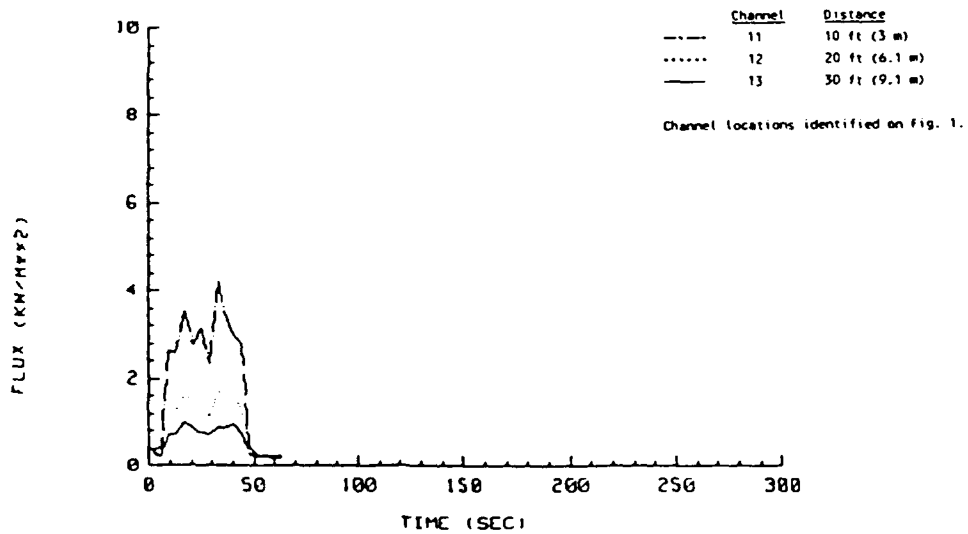

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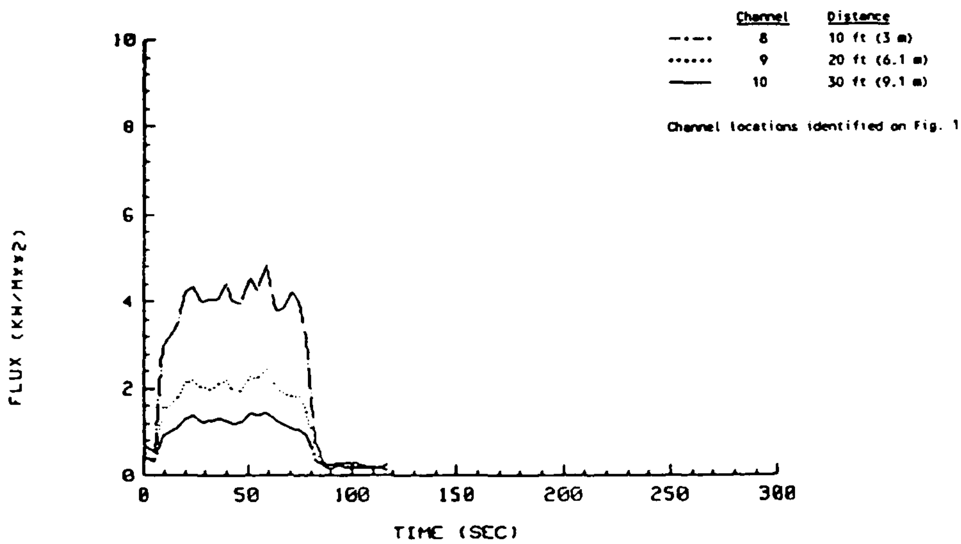

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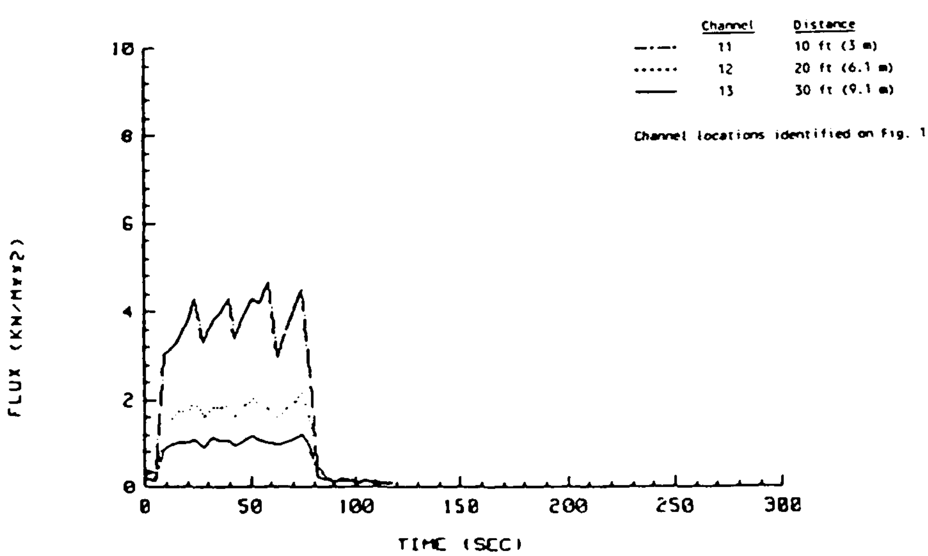

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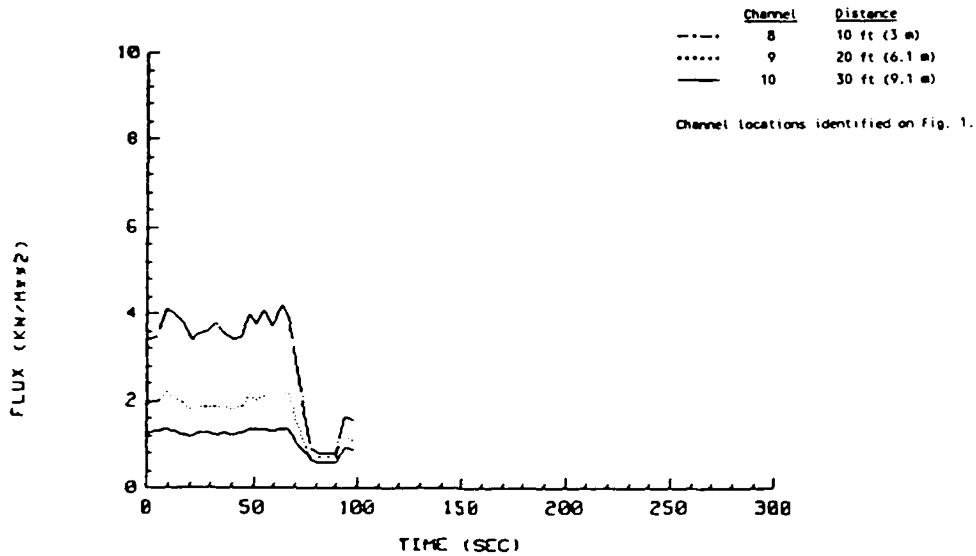

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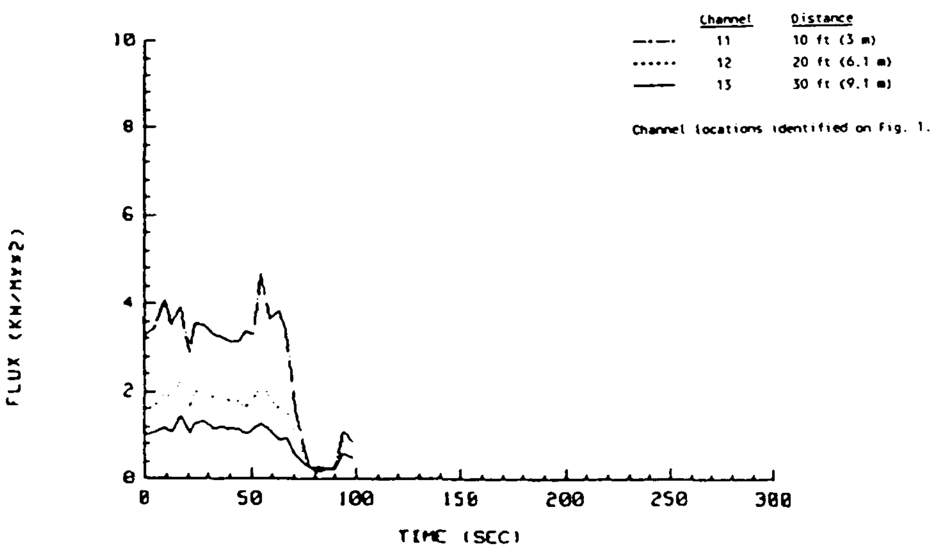

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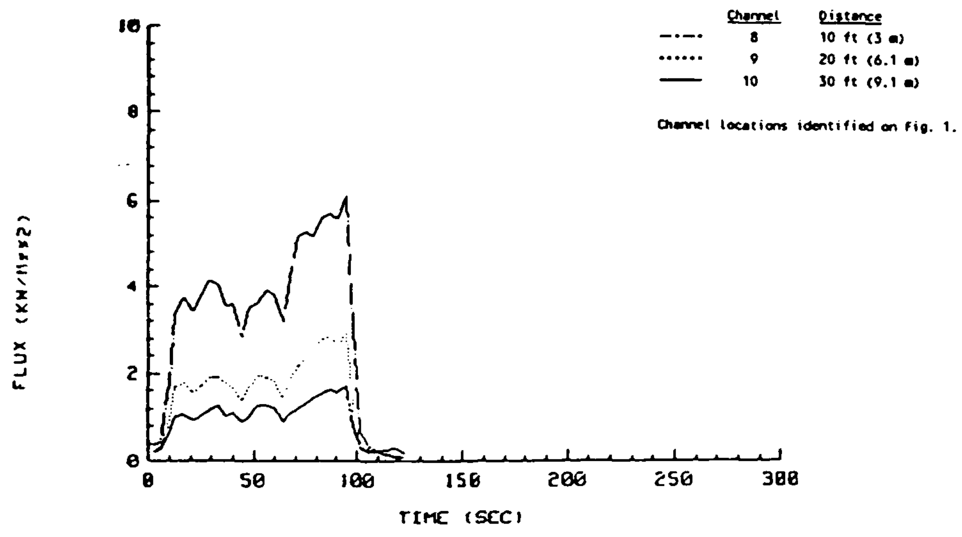

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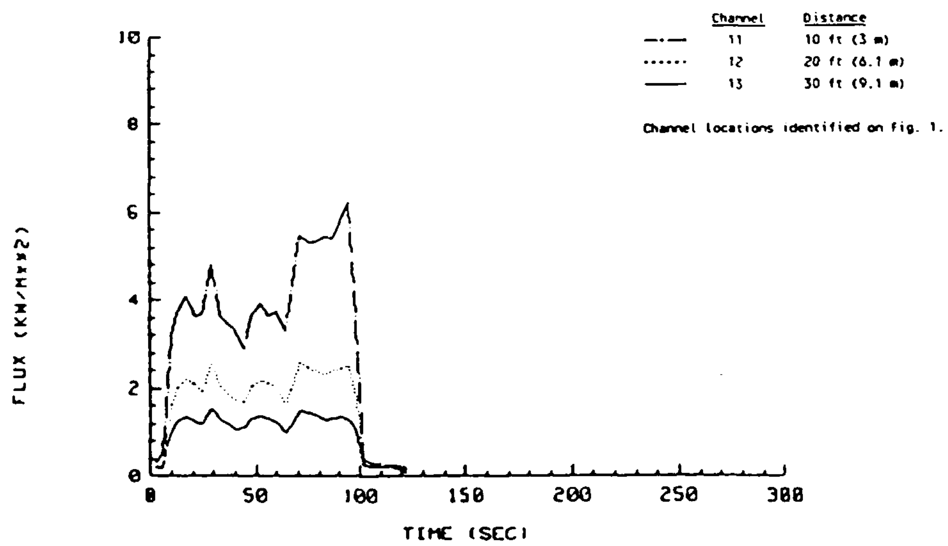

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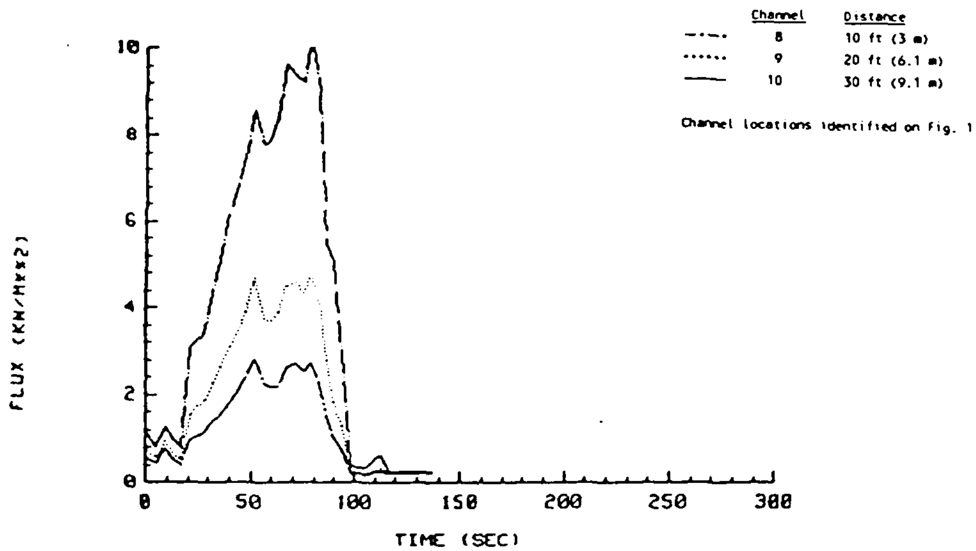

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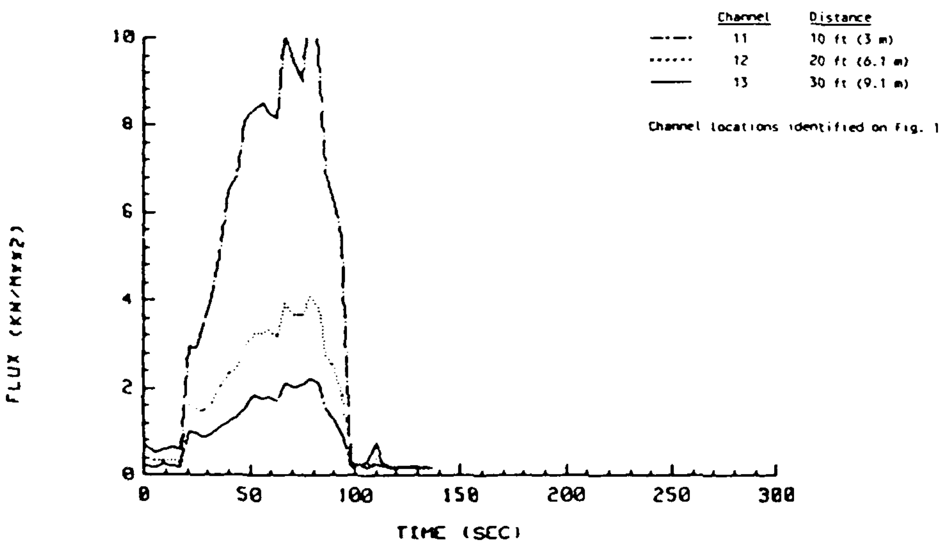

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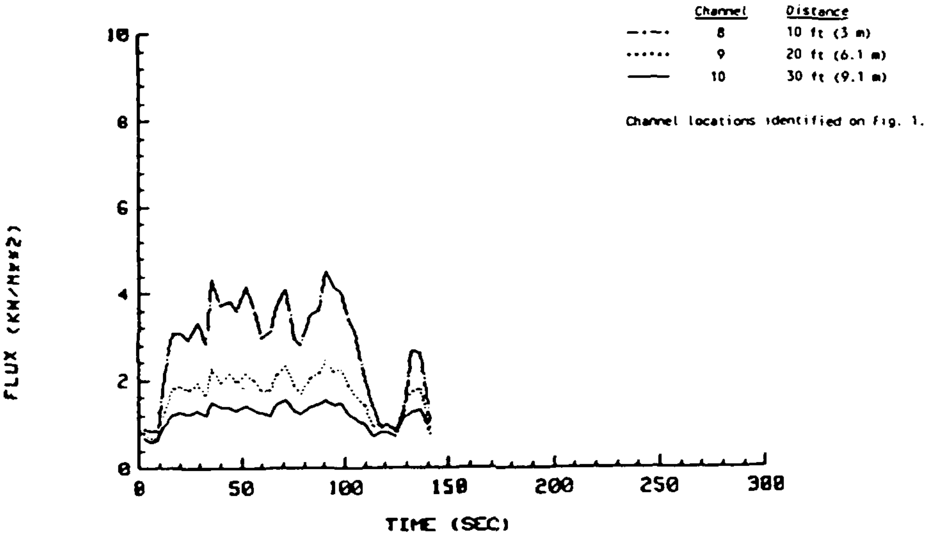

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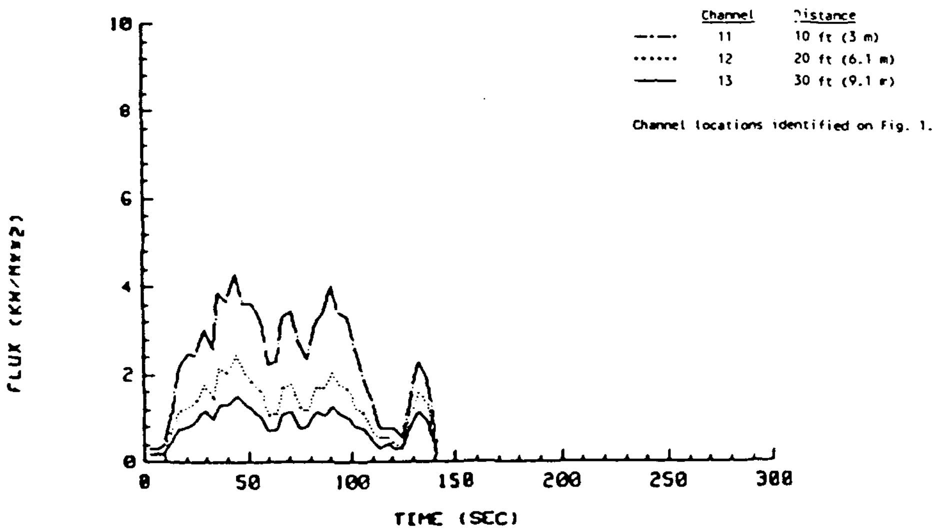

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